

**EFFECTS OF NITROGEN AND IRRIGATION REGIMES ON PERFORMANCE OF
POTATO (*Solanum tuberosum* L.) GROWN IN A MOLLIC ANDOSOL**

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for the Master of Science Degree in Soil Science of Egerton University**

EGERTON UNIVERSITY

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DECLARATION AND RECOMMENDATION

Declaration

I declare that this thesis is my original work and has not been presented in this University or any other for the award of a degree.

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DEDICATION

To my parents, Mr. Gbodja Satognon and Mrs. Elizabeth Azounhoumon.

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ABSTRACT

Nitrogen (N) deficiency in soils and reduced seasonal rainfall contribute to low potato (*Solanum tuberosum* L.) yield in Kenya. Nitrogen deficiency is the major problem faced by the smallholder potato farmers of Kenya due to lack of fallows and knowledge in its management. The objective of this study was to determine the effects of nitrogen and irrigation regimes on the performance of potato grown in a mollic Andosol. Field and rain shelter experiments were conducted for two growing seasons in the research fields of Egerton University, Njoro, Kenya. A randomized complete block design in a split-plot arrangement was used for both experiments. The main plot treatments for the field experiment comprised full supplemental irrigation (FI) and rain-fed potato production (RF). For the rain shelter, the main plot treatments were 100%, 85%, 75% and 50% of the crop evapotranspiration (ETC), where ETC100% was irrigated according to the soil water depletion 2 days after full irrigation. In both experiments, the subplot treatments were 0 (N0), 60 (N1), 90 (N2) and 130 kg N ha⁻¹ (N3) rates. For the field experiment, the results showed the highest tuber yield, 62.12 tonnes per hectare (t ha⁻¹), under FI combined with N3. FI increased marketable yield by about 125.58% in all N treatments compared to RF. The optimum nitrogen use efficiency (NUE), 224.23 kg kg⁻¹ N, was obtained under FI with N3. Application of 130 kg N ha⁻¹ produced the highest water use efficiency (WUE) of 14.24 kg m⁻³. For the rain shelter experiment, potato crop water demand was on average 201.4, 302.1, 342.4 and 402.8 mm under ETC50%, ETC75%, ETC85% and ETC100%, respectively. Potato grown under ETC100% with N3 produced the highest total tuber yield, 58.28 t ha⁻¹, and marketable yield, 54.21 t ha⁻¹. The highest tuber dry matter, 30%, was obtained with 130 kg N ha⁻¹ while the maximum harvest index (HI), 57.12%, and WUE, 17.5 kg m⁻³, were obtained under ETC50% with 130 kg N ha⁻¹. Treatment ETC100% with 90 kg N ha⁻¹ resulted in the highest NUE, 208.30 kg kg⁻¹ N. The correlation coefficients for % N leaf and leaf chlorophyll, and % N leaf and normalized difference vegetation index (NDVI), were highest at 88 ($r = 0.59^{***}$) and 67 days after planting (DAP) ($r = 0.57^{***}$), respectively. A high potato yield in a mollic Andosol can be achieved in Nakuru by introducing FI with an application of 130 kg N ha⁻¹. If maximizing NUE in a mollic Andosol is the purpose of the farmers, then it should be at the expense of potato NUE. Leaf chlorophyll and NDVI can be used for in-season N management at the early growth stages of potato, but the effects of water stress and growth stages of the crop should be taken into account for an accurate N assessment.

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LIST OF ABBREVIATIONS AND ACRONYMS

AUE	Agronomic Use Efficiency
CM-100	CM-100 Chlorophyll Concentration Meter
DAP	Days After Planting
DM	Tuber Dry Matter
ET ₀	Reference Crop Evapotranspiration
ET _a	Cumulative Actual Crop Evapotranspiration
ET _c	Actual Crop Evapotranspiration
FI	Full Supplemental Irrigation
HI	Harvest Index
IWUE	Irrigation Water Use Efficiency
N	Nitrogen
NDVI	Normalized Different Vegetation Index
NUE	Nitrogen Use Efficiency
NUE _e	Nutrient Use Efficiency
RF	Rain-fed Potato Production
WUE	Water Use Efficiency

CHAPTER ONE

INTRODUCTION

1.1 Background information

Potato is the third most important worldwide food crop after rice (*Oryza spp*) and wheat (*Triticum astivum*) (Campos & Ortiz, 2020; FAOSTAT, 2017). Globally, 368 million tonnes were produced in 2018 on an estimated area of 17.58 million hectares (FAOSTAT, 2020). In Kenya, potato is the second most important staple food and cash crop in Kenya, after maize (*Zea mays*). It is mainly cultivated in smallholder farms in the highlands during the rainy seasons. The major growing regions are Nakuru, Nyandarua, Bomet, Meru, Uasin Gishu, Kiambu, Nyeri, West Pokot, Narok, Kericho and Keiyo (Kasina & Nderitu, 2013; Musita *et al.*, 2019). Due to the fast-growing population of Kenya (FAOSTAT, 2020), the high demand for potato in the country has caused encroachment of potato farming into marginal lands, forest reserves, and non-traditional potato-producing areas (Muthoni *et al.*, 2021). Therefore, the area under production increased from 135,000 hectares in 2008 to 217,315 hectares in 2018. Despite the increase in area under production, a yield decline of 60% was registered in 2018 compared to 2008 (FAOSTAT, 2020; Mburu *et al.*, 2020; McEwan *et al.*, 2021). The estimated average yield of 8.6 tonnes per hectare ($t\ ha^{-1}$) obtained in 2018 was very low compared to 40 to 47 $t\ ha^{-1}$ obtained in France and Belgium. The average global yield is estimated at 20.94 $t\ ha^{-1}$ (FAOSTAT, 2020). This makes the country import 50 % of its current potato demand (Muigai, 2013).

Previous research geared toward improving potato productivity in Kenya has focused on controlling pests and improving the fertility of soils (Waaswa *et al.*, 2021), with little attention to water management. Drought or dry periods between rainfall seasons and increased temperatures, which lead to high crop evapotranspiration, are experienced in 70–80% of the smallholder farms in Kenya (Bryan *et al.*, 2013; Kimathi *et al.*, 2021; Muthoni *et al.*, 2017; Taiy *et al.*, 2017). Soils in most potato-growing areas in Kenya are classified as mollic Andosols. Due to their high infiltration rates, these soils are free-draining and become dry a few days after a rainfall event. This makes nutrient and irrigation management difficult for farmers growing potato in mollic Andosols. In Kenya, smallholder farmers rarely irrigate potato due to inadequate knowledge of irrigation practices.

Potato is a water-demanding crop. It requires, on average, 65% moisture content during its growth cycle (Leal Filho *et al.*, 2015; Nowacki, 2018; Kingori *et al.*, 2016). Tolessa (2019) and Djaman *et al.* (2021) estimated potato water demand at 350 to 800 mm depending on the field conditions (Kingori *et al.*, 2016). Tuber initiation to maturity stage forms the critical

water-demand period and water deficits will negatively affect productivity (Ahmadi *et al.*, 2010; Salter & Goode, 1967; Sasani *et al.*, 2006). The main effect of drought or water stress on potato yield is manifested in potato tuber size reduction. Rain-fed potato-growing areas demand additional water through irrigation for uniform wetting to a depth of at least 10–15 cm for high harvests (Yactayo *et al.*, 2009).

Nitrogen (N) is one of the major elements that are usually deficient in potato-growing soils in Kenya. This is due to nutrient depletion as a result of continuous production with inappropriate replenishment (Itabari *et al.*, 2013). N is a vital nutrient for potato due to its positive effect on photosynthetic activities, chlorophyll concentration, plant height, rate of dry matter accumulation and tuber yield (Goffart *et al.*, 2011). For a mature potato crop to yield 25–30 t ha⁻¹, it depletes about 165–200 kg N, 14–17 kg P and 185–225 kg K ha⁻¹ from soil (Baishya *et al.*, 2010). N is, therefore, a very important nutrient in potato production as the value of the other inputs cannot be fully realized unless N is applied to the crop in an optimum amount (Ruža *et al.*, 2013). Because of its short cycle, mineral nitrogen application is necessary to ensure potato productivity since soil nitrogen is largely held up in soil organic matter that cannot be available in high amounts during the potato cycle (Koch *et al.*, 2020).

Nutrients must get to the plant root in order to be absorbed by root hairs. Soil water is a solvent and contains plant nutrients that move within and the soil-water phase. Nutrients dissolved in the soil solution can move either by molecular diffusion due to concentration gradients within the solution or by convection due to the mass transfer of the soil solution. Mass flow is driven by the physiological process of transpiration, where water and dissolved nutrients move from the soil to the surface of the root (Davidson, 2018). Water uptake by roots considerably enhances root N acquisition by mass flow. Water stress reduces the uptake of N by plants as a result of a decrease in water uptake and transpiration rate (Smethurst, 2004). Considerable interest is currently centered around the movement of nitrates through the soil. The reason for this concern is its potential for leaching from the soil profile. The nitrate ion is not adsorbed on the soil matrix and therefore is not retained by the soil (Davidson, 2018).

The N requirement of potato is relatively low during the first 35 days after planting, and high N application during the vegetative growth stage can delay or inhibit potato tuberisation (Jackson, 1999; Zebarth & Rosen, 2007). To replenish the depleted N and ensure a vigorous growth of the crop, the smallholder potato farmers of Kenya apply 80% of the total required N at planting in the form of diammonium phosphate. However, an earlier study in northern China showed that only 20% of total mineral N supplied at planting is taken up by potato crops (Dai *et al.*, 2000). The highest amount of N is required during tuber bulking, which

is the stage at which the plant takes up about 58–70% of the total N from soil (Ojala *et al.*, 1990). Therefore, N management is crucial as it can volatilize or leach out of the soil and the probability that its requirement is the same in different growing seasons is only about 1% (Zheng *et al.*, 2015). In addition, the standard N fertilizer references and recommendations cannot include the spatial and in-season variability in soil N supplying capacity during the crop cycle (Bijay & Ali, 2020; Gabriel *et al.*, 2017). Therefore, a split application method is seen as the best way to increase fertilizer use efficiency under potato production. To avoid N losses or deficits at the time of top dressing and maximize N utilization, the N supply should match the crop's requirements at different stages. The optimization and efficient use of mineral N fertilizers have become the purpose of many researchers in various crops due to their cost-effective and environmental impacts (Muñoz-Huerta *et al.*, 2013). The GreenSeeker sensor and CM-100 concentration chlorophyll meter are mostly used as tools for N recommendation at different stages of various grain crops due to their ease of use and portable aspect. Proper management and coordination of nitrogen fertilizer and irrigation water application can increase potato yield in the face of climate change (Elferink & Schierhorn, 2016).

1.2 Statement of the problem

Population pressure and the need to produce more to satisfy the demand for potato in Kenya have led to encroachment of farming into marginal lands, forest reserves and non-traditional potato-producing areas rather than intensively increasing productivity on the same land. In Kenya, the area under potato production almost doubled between 2008 and 2018. Despite the increase in the cultivation area, potato yield remains low (8.6 t ha^{-1}). Potato is mainly produced during the rainy seasons in Kenya. However, a high frequency of drought due to climate change is experienced in 70–80% of the smallholder farms. N is one of the major elements that are usually deficient in potato-growing soils in Kenya. To replenish the depleted N, the smallholder potato farmers of Kenya apply 80% of the total required N at planting in the form of diammonium phosphate. This fertilizer is associated with a reduction in soil pH as well as several environmental impacts. N losses in the forms of nitrate (NO_3^-) and ammonia (NH_3) occur during heavy rains and drought periods, respectively. All these processes make N fertilizer non-available for potato during its cycle. Inadequate application of N is due to the lack of knowledge on how to match the crop needs with the nutrient supplied. Most of the adaptation measures to increase potato yield in the face of climate change generally focus on soil fertility and potato pests. The effects of both factors were often indicated in literature with dissimilar conclusions and recommendations as the optimum N rates differ across potato

cultivars, soil types, climate and environmental conditions. So far, no study has reported the management of these inputs in potato production in mollic Andosols while using apical rooted cuttings, especially in Kenya. This becomes a great challenge for farmers producing potato in mollic Andosols, which are vulnerable to water infiltration and soluble elements. These disjointed approaches partly contribute to the low potato productivity and quality and the inadequate potato supply to the market. There is, therefore, a research gap that needs to be addressed by determining the effects of nitrogen and irrigation regimes on the performance of potato grown in a mollic Andosols in Kenya.

1.3 Objectives

1.3.1 Broad objective

To contribute to high potato productivity in Kenya by improving nitrogen and irrigation water use efficiency of potato.

1.3.2 Specific objectives

- (i) To determine the effects of supplemental irrigation on the yield, water use efficiency and nitrogen use efficiency of potato grown in a mollic Andosol.
- (ii) To determine the effects of nitrogen and irrigation regimes on the growth and yield of potato grown in a mollic Andosol.
- (iii) To determine the effects of nitrogen and irrigation regimes on nitrogen use efficiency and water use efficiency of potato grown in a mollic Andosol.
- (iv) To determine the possibility of the use of leaf chlorophyll content and normalized difference vegetation index for in-season N assessment and potato yield prediction.

1.4 Hypotheses of the study

- (i) There are no significant effects of supplemental irrigation on the yield, water use efficiency and nitrogen use efficiency of potato grown in a mollic Andosol.
- (ii) There are no significant effects of nitrogen and irrigation regimes on the growth and yield of potato grown in a mollic Andosol.
- (iii) There are no significant effects of nitrogen and irrigation regimes on nitrogen use efficiency and water use efficiency of potato grown in a mollic Andosol.
- (iv) Leaf chlorophyll content and normalized difference vegetation index cannot be used for in-season N assessment and potato yield prediction.

1.5 Justification of the study

Potato is an important source of income for more than 800,000 Kenyan farmers. The potato sector employs more than 3 million people directly and indirectly and contributes to the annual country gross domestic product (GDP) by over Kes. 50 billion. Due to its importance, the government of Kenya has included potato in its priority food crops to fight food security and meet African Agenda 2063 goals. Despite the fact that potato is the most widely distributed crop in tropical and subtropical zones of the world and the second staple food in Kenya, is among the most affected crops by poor irrigation management, mineral fertilization, insect pests, disease infestation, seed potato tuber quality, poor planting dates, and storage conditions. Besides the efforts by the farmers to open more farmlands to grow potato, the production is challenged by a prolonged drought that limits the performance of the crop to their genetic potential. This, together with soil infertility challenges, leads to the recurring low yield obtained mostly by the smallholder farmers. This is due to the inability to provide the crop with timely required growth conditions, including water and nutrients. Introducing supplemental irrigation and off-season potato production through controlled irrigation and fertilizer management can be a great initiative to meet the potato food demand of the country. Water and nitrogen required by potato vary within soil type, and recommendation is based on the soil characteristics and previous crops. Therefore, this study generated knowledge on the specific amount of water and nitrogen required by *Shangi* potato variety grown in a mollic Andosol in Nakuru County. It also provided the knowledge on the possibility of the use of leaf chlorophyll content and normalized difference vegetation index values for nitrogen recommendation in potato production areas of Kenya. These will help farmers maximize nitrogen use efficiency and water use efficiency while achieving an optimum potato yield.

CHAPTER TWO

LITERATURE REVIEW

2.1 Potato production and its importance

After rice (*Oryza sativa*) and wheat (*Triticum aestivum*), potato (*Solanum tuberosum* L.) is the world's third major food crop (Campos & Ortiz, 2020). It is the most important non-cereal crop globally consumed in various forms. Potato production is estimated at 378 million tonnes grown on 19.3 million ha globally (Table 2.1).

Table 2.1: Annual potato production and harvested area in the world (FAOSTAT, 2019)

Region/ Country	2016			2017		
	Harvested area (ha)	Production (tonnes)	Yield (t ha ⁻¹)	Harvested area (ha)	Production (tonnes)	Yield (t ha ⁻¹)
World	18913868	376577033	19.62	19302642	388190674	20.11
Africa	1693219	25196621	13.55	1892633	25011823	13.22
America	1819115	43552328	24.15	1797479	44173458	24.58
Asia	9821664	189623927	18.75	10209139	195668682	19.17
Europe	5540384	116573050	21.46	5365045	121761565	22.70
East Africa	632367	7199827	9.41	754116	7199596	9.55
Belgium	89164	3402787	38.16	92855	4416665	47.57
France	175225	6834680	39.01	173486	7342203	42.32

Potato is mostly produced in the northern hemisphere and in the temperate zone, where the crop does best during the frost-free periods of summer. In these regions, potato is grown primarily as a cash crop, and hence it is a major income source (Campos & Ortiz, 2020). In the tropics, the crop is mostly grown in the volcanic mountains of West Africa and Southeast Asia, in the highlands of the Andes, in the African highlands and in the Rift Valley where production is for both cash and food (Mbiyu *et al.*, 2012; Muthoni & Kabira, 2010).

Potato is grown as a winter crop in the subtropics to take advantage of the heat-free periods of the year. The subtropical nations include North India, the Mediterranean region and southern parts of China. The high temperatures in the tropical lowlands are responsible for potato not being the main staple crop. These conditions limit growth and tuber development in some potato cultivars, mostly the traditional cultivars (Haverkort *et al.*, 2013). Given the large number of hectares harvested and tonnes produced, potato is ranked among the fastest-growing food crops (FAOSTAT, 2019).

Potato production has also been adopted in non-traditional areas of Africa. The region has a wide range of climatic conditions, including the highlands of Eastern and Central Africa to Egypt and South Africa in the south. The rate of potato production in Africa has greatly increased. For example, in 2016, Egypt emerged as the 8th highest exporter of both raw and processed potato worldwide (Mulugeta *et al.*, 2019). There has been an impressive increase in East African potato production in recent years, indicating its significant contribution to local food systems. For example, in Tanzania, the potato supply almost tripled between 2000 and 2014 (Campos & Ortiz, 2020; FAOSTAT, 2019). In Rwanda, approximately 125 kg per capita was consumed per year, and this led to the inclusion of potato in the national priority list of crops owing to its role in national food security (FAO, 2009). In Kenya, potato is mainly grown in the highlands (1.7–3.0 km above sea level) (Gitari *et al.*, 2018). It is a cash and food crop, thus contributing significantly to the Kenyan economy. Indirectly it employs about 2.5 million people throughout the entire value chain. In 2017, the harvested area was about 10% of Africa’s harvested area, producing 1.52 million tonnes (Table 2.2). Its importance has increased because of its food supply per capita per day which was constant between 2015 and 2017, besides the growing population in Kenya (FAOSTAT, 2019).

Table 2.2: Harvested area, productivity and production trend of potato between 2010 and 2018 in Kenya (FAOSTAT, 2020)

Years	harvested area (ha)	Yield t ha ⁻¹)	Production (tonnes)
2010	121542	22.43	2725936
2011	123390	19.17	2365263
2012	143325	20.34	2915067
2013	152007	14.43	2192885
2014	115604	14.07	1626027
2015	133532	14.70	1963495
2016	145967	9.15	1335883
2017	192341	7.90	1519870
2018	217315	8.61	1870375

2.2 Origin and taxonomy of potato

Potato originated from the Andean highlands, where farmers started domesticating the tuber crop adjacent to Lake Titicaca in the southeast parts of Peru about 8000 years ago. In the 16th century, the Spanish explorers took the potato back to Europe and since then, it is

cultivated worldwide (de Haan & Rodriguez, 2016; Gnanasekaran & Basalingappa, 2018; Hawkes, 1990). The central highlands of Mexico are considered as a centre of genetic diversity for both the potato late blight pathogen (Flier *et al.*, 2003) and germplasm of tuber-bearing *Solanum sp.* (Razdan, 2005). Up to this date, there still exists a wide variety of wild relatives of the species with a great diversity in this region. It grows up to 90–100 cm tall, producing white and pink or purple flowers with yellow stamens 3–4 weeks after sprouting. Potato is an herbaceous annual plant. It has weak stems that are angular and may be solid or hollow due to the disintegration of pith cells and it produces a tuber that is commonly known as potato, which is rich in starch (Flier *et al.*, 2003).

Potato is among the estimated 2,300 species in the family Solanaceae. The Solanaceae family consists of about 90 genera, the genus *Solanum* being the largest, which includes about 1,500 species, including nicotiana (*Nicotiana tabacum* L.) tomato (*Solanum lycopersicum* L.), eggplant (*Solanum melongena* L.) and pepper (*Capsicum annum* L.) (Lim, 2012a). Potato is a dicotyledonous plant with the characteristics of all dicotyledons. These include the possession of stems with vascular bundles placed in a circular arrangement and containing the cambium layers, i.e., the xylem and phloem (Chen *et al.*, 2019b; O'Keeffe, 2019). Its chromosome numbers vary from diploid, triploid, tetraploid, pentaploid to hexaploid with $2n = 2x = 24$, $2n = 2x = 36$, $2n = 4x = 48$, $2n = 5x = 60$ and $2n = 6x = 72$, respectively (Brücher, 2012; de Haan & Rodriguez, 2016; Panahandeh, 2019). Botanically improved potato cultivars today domesticated in North America, Europe and other parts of the world, including Africa, are classified as *Solanum tuberosum* L. (William & Steven, 2010). Despite being of southern Peru origin, modern cultivars grown worldwide emanate from the landraces of the Chilean (de Haan & Rodriguez, 2016).

Potato is an annual crop, although it can vegetatively persist in the field as tubers from one season to another. Commonly grown varieties in Kenya include Tigoni, Asante, Sherekea, Kenya Mpya, Robijn, However, *Shangi* and Dutch (NPCK, 2017). The *Shangi* variety is the most popularly consumed (42%), followed by the Tigoni variety (27%) (Janssens *et al.*, 2013; Mumia *et al.*, 2018). Kenyan consumers have a strong desire for *Shangi* rather than other varieties because it takes a short time to cook. Farmers in Kenya mainly produce the *Shangi* variety because it is an early maturing and high-yielding variety.

2.3 Challenges in potato production

The Kenyan national average for potato yields is estimated at 7.7 t ha^{-1} , but due to several challenges, this figure varied considerably in past years, fluctuating from 9.5 t ha^{-1} to

around 7.5 t ha⁻¹ (Kaguongo *et al.*, 2013; Ogalleh *et al.*, 2012). The common challenges of potato production include bacterial wilt (*Pseudomonas solanacearum*), late blight, lack of proper pest and disease management measures by the smallholder farmers and lack of viable planting materials (Muthoni *et al.*, 2013). Global warming presents a significant challenge that constrains potato production. Potato grown in warm tropical areas succumb more to the effects of climate change like uneven rainfall patterns and prolonged sunshine that results in dry spells. The crop requires a mean daily temperature range of 18–20 °C and less than 15 °C for nighttime temperatures, but it performs well at 20–25 °C and below 20 °C for day and night, respectively (Kumar *et al.*, 2015). Such temperature conditions favour growth and tuberization. Daily night temperatures of 23 °C and above limit tuber formation. This makes the crop vulnerable to heat due to its narrow production window (Menzel, 1980). Water stress and any temperature rise lead to low tuber quality and yield losses, and before tuber development, lower tuber number per plant. Excess or low soil moisture causes remarkable yield losses because potato quickly responds to changes in precipitation regime (Karanja *et al.*, 2014; Muthoni *et al.*, 2017). The irregular rainfall poses a challenge to potato smallholder farmers since it prevents the timely application of fertilizers that may translate into higher yields (Mugagga *et al.*, 2019).

2.4 Soil requirements for potato growth

Potato does well on a wide range of soils, except waterlogged soils. Potato requires well-aerated, permeable and deep soils (Lim, 2012a). Loose, friable and mineral or organic well-drained soils with medium loam or silty textures of a pH range of 4.8 to 7 also favour potato growth. Lower pH of 4.7 and below results in impaired growth (Lim, 2012a). Tuber yield and quality are directly impacted by the timing and amount of soil nutrients provided to the crop, and therefore effective management of soil nutrients is key to potato production. Potatoes are heavy feeders and hence with higher nutrient demands. For a mature potato crop to yield 25–30 t ha⁻¹, it depletes about 165–200 kg N, 14–17 kg P and 185–225 kg K ha⁻¹ (Ghosh, 2015; Koch *et al.*, 2020).

2.5 Effect of N on growth and yield of potato

The use of NPK fertilizers and other sources of nutrients from other soil amendments and minerals enhances soil nutrient status for crop production. Inorganic nitrogen is necessary for potato productivity due to its mobility in soils and the huge amounts required by the crops during their cycles (Bucher & Kossmann, 2007; Silva *et al.*, 2013). Owing to its short cycle, an inorganic source of N is necessary to ensure potato productivity as soil N is widely tied up

in organic matter (Koch *et al.*, 2020). The amount of N required by potato depends on the potato variety and the soil type. The daily N requirement at the tuber bulking stage varies between 3 and 4.5 kg N ha⁻¹ depending on the potato variety. About 58–70% of the total nitrogen supplied is taken up during the development stage of the plant (Ojala *et al.*, 1990). Increasing the N application can enhance potato yield by increasing the tuber size. N deficiency is manifested by reduced growth and results in reduced tuber yield in terms of tuber number and size (Koch *et al.*, 2020). This deficiency can be caused by several factors, including soil pH (low or high), drought conditions or heavy irrigation and low soil organic matter. However, excess N during the vegetative growth of potato delays the tuber initiation and its maturity and increases aboveground biomass (Koch *et al.*, 2020; Lim, 2012b; Painter & Augustin, 1976). Agronomic use efficiency (AUE) of the potato crop is well known to be low, ranging between 50 and 60%. This implies that meeting the actual N demand of the crop during its cycle, split application of N is seen as the best approach (Ghosh, 2015; Gitari *et al.*, 2018; Rens *et al.*, 2016). This approach can reduce the risk of N leaching, especially in irrigated potato production on sandy soils (Errebhi *et al.*, 1998) and meet the crop demand at the different growth stages (Ojala *et al.*, 1990).

2.6 Effect of irrigation on growth and yield of potato

Potato crop is sensitive to water deficit. It needs about 25–50 mm of water per week, and this leads to crop response with an increase in yield up to 2 t ha⁻¹ for each 20 mm of applied water (Asfary *et al.*, 1983; Fabeiro *et al.*, 2001). The water demand ranges from 350 to 800 mm during the growing season, depending on the soil type, cultivar, growing period and environmental field conditions (Al-Gaadi *et al.*, 2016; Djaman *et al.*, 2021; Sasani *et al.*, 2006; Sood & Singh, 2003). Rain-fed potato-growing areas demand additional water supplements through irrigation for uniform wetting to a depth of at least 10–15 cm for bumper harvests (Yactayo *et al.*, 2009). According to Leal Filho *et al.* (2015), drip irrigation has increased potato productivity because furrow irrigation usually requires larger amounts of applied water to adequately wet an entire field rather than drip or sprinkler irrigation methods.

Reducing water supply (once every 3–5 days) is required during the maturity stage of the plant to allow efficient root respiration. Efforts to increase the water use efficiency of potato have devised micro-irrigation, which often improves crop production and quality through the direct supply of the amount of water required by the plant. However, this method is known to favour salt accumulation in the upper portion of the root zone, which may constrain crop growth (Özkaynak & Samanci, 2005). The study findings by Liu *et al.* (2007) in Denmark found that

irrigation water use efficiency (IWUE) was 829 and 479 kg m⁻³ for partial root dry and full irrigation, respectively. There was 30% of irrigation water saved on partial root dry compared to full irrigation.

2.7 Interaction effect of N and irrigation on the growth and yields of potato

In the subtropical plains, potato, a short-duration heavy feeder crop, takes between 90 to 100 days to produce 25–30 t ha⁻¹ tubers. Efficient and balanced use of water and nutrients results in increased potato yields. A monitored drip system that allows nutrification is the preferable method of potato irrigation on sandy soil. It helps to split N according to the plant needs in order to avoid intoxication of N. Integrating N with irrigation water significantly affects NUE. Application of irrigation water where a low nitrogen rate of 0 kg N ha⁻¹ is supplied leads to 0 kg kg⁻¹ N of NUE (Koch *et al.*, 2020). NUE increases with irrigation water. High irrigation water application results in better NUE compared to low irrigation water. Increasing the irrigation rate from 40 to 100% increases NUE by 14.42 and 13.3 kg kg⁻¹ N. Generally, the application of N beyond 112.5–150 kg N ha⁻¹ decreases NUE by 14.48 kg kg⁻¹ N (Koch *et al.*, 2020). Water and nitrogen are two critical factors in potato production. Since potato is sensitive to water deficit, even slight water stress causes a reduction in leaf number and size, canopy radiation interception and photosynthesis, which consequently affects the tuber number, size and yield. In agricultural production, the influences of water and N on plant growth are not independent. Water stress reduces N uptake as a result of a decrease in water uptake and transpiration rate. In the absence of proper management, the high amount of N and gravitational water increases N losses under potato irrigation (Cambouris *et al.*, 2008; Giletto *et al.*, 2019; Giletto & Echeverría, 2013b; Vos, 2009).

2.8 Correlation between normalized difference vegetation index (NDVI), leaf chlorophyll and leaf N

Normalized difference vegetation index (NDVI) is used for the quantification of vegetation by measuring the difference between the near-infrared (NIR) (which vegetation strongly reflects) and red light (which vegetation absorbs). The NDVI is calculated by measuring the reflectance in the red and near-infrared (NIR) part of the spectrum, which is computed as follows:

$$NDVI = \frac{RNIR - RRed}{RNIR + RRed} \dots\dots\dots \text{Equation 2. 1}$$

Where; RNIR = reflectance of NIR radiation, and RRed = visible red radiation. It ranges from -1 to $+1$, and it measures a distinction in the different land cover types. For example, negative values may indicate that the area is occupied by water. On the contrary, NDVI values that are close to $+1$ show a high possibility of dense green leaves. However, a figure close to zero may mean no green leaves, and it could also mean that the area is urbanized (Govaerts & Verhulst, 2010). It measures this by computing the reflectance in the red and near-infrared (NIR). Bala *et al.* (2007) found a direct correlation between spectral reflectance, agronomic and biophysical parameters of the plant related to photosynthetic processes and crop yield (Ma & Veroustraete, 2006).

The chlorophyll content determines the photosynthetic activity. The relationship between the leaf chlorophyll and nitrogen has been demonstrated for wheat (Bojović & Marković, 2009; Wood *et al.*, 1993) and maize (Blackmer & Schepers, 1995; Blackmer *et al.*, 1994). The NDVI has been attributed to variables such as crop nutrient deficiency, grain yields, long period water stress, total biomass and canopy density (Bala *et al.*, 2007). For example, in a field condition where N affects plant growth, the NDVI may strongly correlate with soil N. However, where water is the limiting growth factor, the NDVI may strongly correlate with the available soil moisture. Giletto and Echeverría (2013b) reported that potato cultivars subjected to water deficits positively correlated NDVI and yield. Different studies by Giletto and Echeverría (2013b) indicated that the increase in near-infrared radiation (NIR) reflections increased with the dosage of N fertilizer applied. This, together with the findings of Gómez *et al.* (2019), indicated that potato plants with lower nitrogen contents had lower NDVI values (0.82) as compared to potatoes grown under optimal nitrogen conditions (NDVI = 0.88).

2.9 Nutrient use efficiency (NUEe)

Generally, efficiency is defined as the achievement of a planned outcome with minimal possible input of costs. While the input in the concept of nutrient use efficiency (NUEe) is nutrients, there is a need for further investigation to specify the planned outcome (Reich *et al.*, 2014). John *et al.* (2019) defined NUEe as the ability of the crop to take nutrients from the soil that is limited in a given element to produce a high yield (root or shoot biomass). Universally, NUEe can be divided into two main components at the plant level: (1) the efficiency in nutrient acquisition and (2) the efficiency with which the nutrient is utilized to produce the desired yield (Hawkesford *et al.*, 2016). Figure 2.1 shows the process of nutrient (inputs) transformation into output.

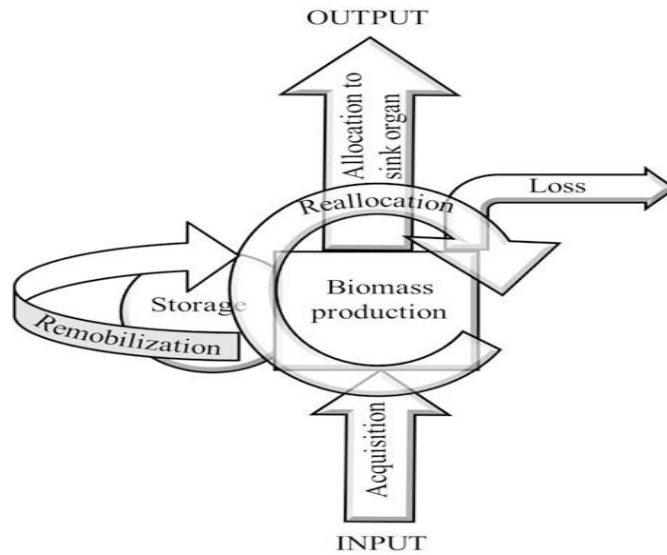


Figure 2.1: Mechanism by which plants convert nutrient uptake into the product (Reich *et al.*, 2014).

NUEe is severely influenced by physiological and genetic components that affect the crop’s ability to absorb and use nutrients under varying ecological and environmental conditions (Rakshit *et al.*, 2015). According to Imran *et al.* (2016), nutrient-efficient crop varieties or genotypes within species are those that produce high dry matter or have a greater increase in harvested biomass per unit applied nutrient area and time, and they exhibit fewer deficiency symptoms with higher mineral nutrient concentrations than other crops or genotypes grown under the same conditions. NUEe of plants grown in soil is controlled by (a) the ability of the soil to release the nutrients, (b) the ability of the plants to absorb and utilize the nutrients and (c) the utilization efficiency (based on remobilization of the nutrients) (Baligar & Fageria, 2001). It is explained by many formulae depending on the crop and the nutrient. The first formula used for NUEe estimation is agronomic use efficiency (AUE) which is defined as the economic production (yield) gotten per unit of nutrient applied (Equation 2.2).

$$AUE = \frac{Y_{fp} - Y_{up}}{Q} \dots\dots\dots \text{Equation 2. 2}$$

Where; AUE is the agronomic use efficiency (kg kg⁻¹), Y_{fp} is the yield of the fertilized plot (kg), Y_{up} is the yield of the unfertilized plot (kg) and Q is the amount of nutrient applied (kg).

AUE is mainly influenced by the soil type, climate, plant, and social-economic situation of the farmers. Nutrient efficiency ratio (NER) is also one of the NUEe parameters used to differentiate genotypes into efficient and inefficient nutrient utilizers (Baligar *et al.*, 1989; Brücher, 2012; El Bassam *et al.*, 2012). It is estimated using the following equation (Baligar *et al.*, 1989):

$$NER = \frac{Y}{q} \dots\dots\dots \text{Equation 2. 3}$$

NER is the nutrient efficiency ratio (kg kg⁻¹), Y is the total yield (kg), (kg) and q is the total amount of nutrients in the plant tissues (kg).

The previous studies have shown several methods to assess nutrient use efficiency in various crops. Among these methods, the most cited are apparent recovery efficiency (ARE) (equation 2.4), physiological efficiency (PE) (equation 2.5), utilization efficiency (UE) (equation 2.6) and agro-physiological efficiency (APE) (equation 2.7). Each method implies several factors and depends on the environment, soil types and crop.

$$ARE (\%) = \frac{NUf - NUuf}{Q} \dots\dots\dots \text{Equation 2. 4}$$

Where; NUf and NUuf are the nutrient uptake (kg) by total biomass at the harvest on fertilized and unfertilized plots, respectively and Q = amount of nutrient applied (kg).

$$PE = \frac{BYf - BYuf}{NUf - NUuf} \dots\dots\dots \text{Equation 2. 5}$$

Where; BYf and BYuf are the biological yield (total biomass at the harvest) of fertilized and unfertilized plots (kg), respectively, while NUf and NUuf are the nutrient uptake in the total biomass at the harvest of the fertilized and unfertilized plots (kg), respectively.

$$UE = PE \times ARE \dots\dots\dots \text{Equation 2. 6}$$

$$APE = \frac{GYf - GYuf}{NUf - NUuf} \dots\dots\dots \text{Equation 2. 7}$$

Where; GYf and GYuf are the grain or tuber yield of fertilized and unfertilized plots (kg), respectively, while NUf and NUuf are nutrient uptake in the total biomass at the harvest of fertilized and unfertilized plots (kg), respectively (Baligar & Fageria, 2001; Hawkesford *et al.*, 2016; Lyons *et al.*, 2018; Rakshit *et al.*, 2015).

NUEe has mostly been manipulated on major grain crops (maize, rice, wheat) due to their importance in food security. Most of these equations have been developed based on the NUE since N is likely considered as one of the major elements that limit agricultural productivity due to its mobility in soil. Nitrogen compounds that are usually used as chemical fertilizers are generally mobile in the soil, and only 30–40% of the amount applied is taken up by plants (Van Oosten *et al.*, 2019). The previous research showed that nitrogen recovery efficiencies in research-managed experiments for these major grain crops range from 46 to 65% (Rakshit *et al.*, 2015). A review indicated that the average nitrogen recovery efficiency in the field ranges from about 20 to 30% under rain-fed agriculture and 30 to 40% under irrigated agriculture (Rakshit *et al.*, 2015). N fertilizer recovery under different cropping systems is

about 37% recovery for corn (Cassman *et al.*, 2002). Rakshit *et al.* (2015) found that the average N recovery ranges from 31% for irrigated rice grown by Asian farmers and 40% for rice under field-specific management compared to on-farm nitrogen recovery efficiencies that range from 20–to 40%. This is due to the environmental losses that remain an agricultural challenge. Reduction of losses due to the environment can only be achieved by studies that target local context or specific vulnerability of low nutrient impacts and come up with recommendations for the specific spatial and temporal amount of nutrient. Nitrate translocation efficiency and assimilatory reduction determine the ability of the plants to uptake nitrate (Van Oosten *et al.*, 2019).

2.10 Nitrogen use efficiency of potato

Potato nutrient demand varies within varieties, in space and with time. A study conducted by Trehan and Kumar (2015) on five varieties/cultivars such as K. Pukhraj, K. Sutlej, K. Bahar, K. Ashoka, and K. Sindhuri found that cultivars with higher nitrogen efficiency took up more nitrogen per unit of soil compared to less N-efficient cultivars. Higher efficient uptake (171–214 kg kg⁻¹) was recorded from cultivars like K. Pukhraj, while low efficient uptake (139–149 kg kg⁻¹) was mostly shown by K. Bahar and K. Ashoka cultivars (Trehan & Kumar, 2015). This shows the different requirements of potato varieties in terms of nutrition (Hawkesford *et al.*, 2016). The highest NUE value of 176 kg kg⁻¹ N was obtained from full irrigation plots (Badr *et al.*, 2012). Fandika *et al.* (2016) and Liu *et al.* (2012) found that NUE increased with the increase in irrigation amount. Fandika *et al.* (2010) reported that NUE increment depended on the potato genotype. Increasing irrigation amount from ETC60% to ETC100% could increase potato NUE by 26.2 to 104.2%, depending on the genotype and the soil type. On the contrary, Djidonou *et al.* (2013) reported an increase in potato NUE with reduced irrigation amount. NUE can also be affected by the N status of the growing soil. Badr *et al.* (2012) and Tolessa *et al.* (2017). Ierna and Mauromicale (2019) reported the highest potato NUE when applying 100 kg N ha⁻¹. Ospina *et al.* (2014) indicated that potato NUE generally decreases with an increase in N dosage. However, some potato varieties presented an increase in NUE with an increase in N rate up to 180 kg N ha⁻¹. Maltas *et al.* (2018) recorded the highest potato NUE at 120 kg N ha⁻¹. Badr *et al.* (2012) and Zotarelli *et al.* (2008) explained this decrease in potato NUE with N dosage by the ability of potato to extract more N from the soil when it is grown in a nitrogen-limited soil. Tolessa *et al.* (2017) indicated that the N rate did not affect potato NUE. Potato NUE is also influenced by soil type, soil depth and drainage, and other nutrient statuses in the growing soil (Maresma *et al.*, 2016). Defining

upper limits of nitrogen uptake and nitrogen use efficiency of potato in response to crop nitrogen supply is essential to enhance crop productivity.

CHAPTER THREE
EFFECTS OF SUPPLEMENTAL IRRIGATION ON YIELD, WATER USE
EFFICIENCY AND NITROGEN USE EFFICIENCY OF POTATO GROWN IN A
MOLLIC ANDOSOL

Abstract

Low soil fertility and reduced seasonal rainfall contribute to low potato (*Solanum tuberosum* L.) yield in Kenya. The objective of this study was to determine the effects of supplemental irrigation and N-fertilization rates on tuber yield, NUE and WUE of potato grown in a mollic Andosol in Nakuru, Kenya. The soils of the experimental site are classified as mollic Andosols. A randomized complete block design (RCBD) in a split-plot arrangement was used. The main plot treatments comprised two irrigation treatments: full supplemental irrigation (FI) and rain-fed potato production (RF). The subplot treatments were four N rates: 0 (N0), 60 (N1), 90 (N2) and 130 kg N ha⁻¹ (N3). The results showed that total tuber yield, marketable tuber yield and NUE were significantly ($P < 0.001$) affected by irrigation×nitrogen while WUE was only affected ($P < 0.001$) by N-fertilization. The highest total tuber yield, 62.12 t ha⁻¹, was obtained under FI combined with N3. Treatment FI significantly increased marketable tuber yield by approximately 125.58% in all N treatments compared to RF. The highest NUE of potato (236.44 kg kg⁻¹ N) was found under FI combined with N3, but it was not significantly different from the NUE of potato obtained under FI with N2. N-fertilization N3 produced the highest WUE of 14.24 kg m⁻³. Significant correlations were obtained between tuber yield and number of tubers per plant ($r = 0.75^{***}$), NUE ($r = 0.95^{***}$) and WUE ($r = 0.72^{***}$). High potato yield and marketable tuber yield in a mollic Andosol can be obtained when water deficits of the growing season are eliminated with supplemental irrigation and application of 130 kg N ha⁻¹.

Keywords: N-fertilization, NUE, Potato, Supplemental irrigation, WUE, Yield

3.1 Introduction

Potato (*Solanum tuberosum* L.) is the second most important staple food and cash crop in Kenya after maize (*Zea mays*) (Muthoni *et al.*, 2017; Waaswa and Satognon, 2020). Its production is predominantly rain-fed (Muthoni *et al.*, 2021). Population pressure and the need to produce more to satisfy the demand for potato have led to encroachment of farming into marginal lands, forest reserves and non-traditional potato-producing areas (Muthoni *et al.*, 2021). In Kenya, the area under production increased from 135,000 ha in 2008 to 217,315 ha in 2018. Despite the increase in the area under production, a low yield of 8.6 t ha⁻¹ was obtained

in 2018, registering a decline of 60% from 2008 (FAOSTAT, 2020; Mburu *et al.*, 2020; McEwan *et al.*, 2021). Drought or dry periods between rainfall seasons and increased temperatures, which lead to high crop evapotranspiration, are experienced in 70–80% of the smallholder farms in Kenya (Bryan *et al.*, 2013; Kimathi *et al.*, 2021; Muthoni *et al.*, 2017; Taiy *et al.*, 2017). Soils in most potato-growing areas in Kenya are classified as mollic Andosols. Due to their high infiltration rates, these soils become dry a few days after a rainfall event. Potato is sensitive to water deficit, and slight water stress causes a reduction in leaf number and size, canopy radiation interception and photosynthesis, which consequently affects the tuber number per plant, size and yield (Li *et al.*, 2016). Supplemental irrigation is a perfect technique to cope with the effect of climate variability in Kenya. In supplemental irrigation, water is supplied to essentially rain-fed crops during the period when precipitation fails to uniformly provide sufficient amounts of water required by the crop to fully produce its potential yield. This method helps to maintain the soil moisture at a high level and eliminate the water deficit in the plant root zone. Research conducted in China showed that 55 mm of supplemental irrigation could increase potato yield up to 50.8% (Tang *et al.*, 2018).

Due to the lack of fallow, nitrogen deficiency is another major problem the smallholder potato farmers face in Kenya. Nitrogen deficiency is manifested by reduced growth and tuber yield in terms of tuber number per plant and size (Koch *et al.*, 2020). It is well known that soil water affects nutrient transport to the root surface in the water flux created by transpiration (mass flow) (Smethurst, 2004) and high water uptake by plant roots considerably enhances root N acquisition by mass flow (McMurtrie & Näsholm, 2018). Water stress reduces N uptake as a result of the decrease in water uptake and transpiration rate (Koch *et al.*, 2020). Hence, suppressing water stress in the root zone during the growing season can improve N uptake by potato crops. The objective of the study was to determine the effects of supplemental irrigation and N-fertilization rates on tuber yield, NUE and WUE of potato grown in a mollic Andosol in Kenya.

3.2 Materials and methods

3.2.1 Experimental site

A two-season field experiment was conducted between July 2020 and January 2021 at the experimental farm of Agro-Science Park, Egerton University in Nakuru County, Kenya. The experimental site is located in agro-ecological zone III of Kenya (0.3031° S, 36.0800° E) at an altitude of 2670 m above sea level. Climatic factors, including precipitation (Figure 3.1), maximum and minimum temperature and humidity of the growing seasons (Table 3.1) were obtained from the weather station of Egerton University, located 1 km away from the experimental site. Maize, beans (*Phaseolus vulgaris*), wheat and potato are the most common crops grown in the study area. The soils at the experimental site are well-drained, with dark reddish clays, and slightly acidic. They contain medium levels of organic carbon and low levels of phosphorus, and they are classified as mollic Andosols (Jaetzold *et al.*, 2007).

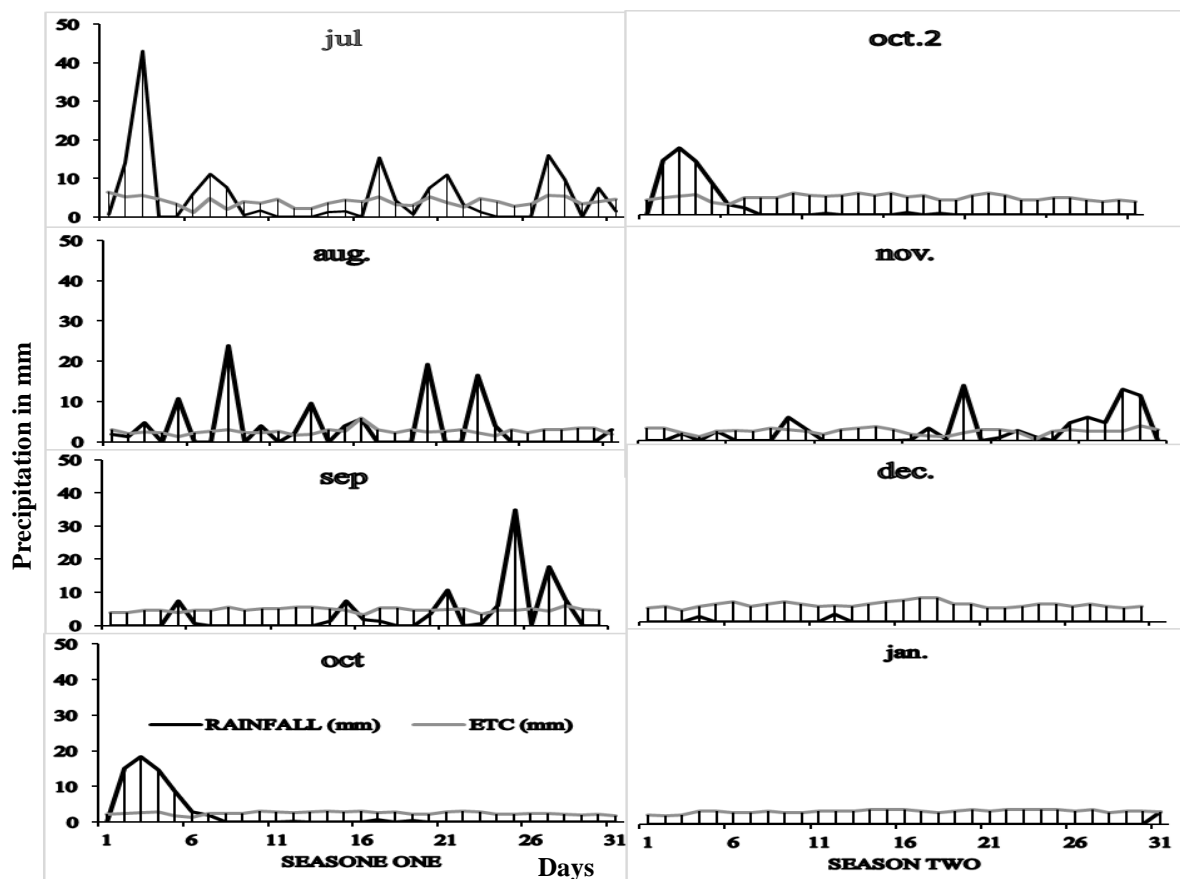


Figure 3.1: Daily precipitation and ETC of the growing seasons at Egerton University.

Table 3.1: Meteorological data from the weather station of Egerton University.

Parameters	Jul	Aug	Sep	Oct	Nov	Dec	Jan
Average of maximum temperature (°C)	23.2	23.8	24.1	25.2	23.4	27.2	26.1
Average of minimum temperature (°C)	10.5	10.7	9.5	10.1	10.2	9.9	10.0
Average of humidity (%)	49.0	48.0	51.0	49.0	49.0	53.0	57.0

3.2.2 Physico-chemical analysis of soil at the experimental site

To determine initial soil properties, soil samples were randomly taken in a zig-zag pattern from six locations in the experimental area before the treatment layout at two different depths (0–0.15 m and 0.15–0.45 m) since the potato root zone falls at 0–0.4 m. The collected samples were mixed to obtain one composite sample per depth. The composite samples were air-dried at room temperature (22–25 °C) for a week, crushed and sieved through a 2-mm sieve. The baseline soil physical and chemical analyses were performed at the soil testing laboratories of Kenya Agricultural and Livestock Research Organization (KALRO), Nairobi. For the physical properties of the experimental soil, soil texture, with the percentage of each primary soil (sand, silt and clay), was determined using the hydrometer method (Bouyoucos, 1962). Soil bulk density (ρ_b) of samples collected at the two different depths using core rings was determined using the gravimetric method followed by the oven drying method (Blake, 1965). Field capacity (FC) was assessed by subjecting the composite samples to pF 2.5, followed by the oven drying method (at 105 °C to constant weight) (Aschonitis *et al.*, 2013). Permanent wilting point (PWP) was measured after subjecting the samples to a pF of 4.2, followed by the oven drying method (at 105 °C to constant weight). Available water (AW) was then computed by subtracting PWP from FC using equation 82 of FAO 56 (equation 3.1) (Allen *et al.*, 1998).

$$AW = 1000(\theta_{FC} - \theta_{WPP})Z_r \dots\dots\dots \text{Equation 3. 1}$$

Where; AW = total available soil water in the plant root zone (mm), θ_{FC} = water content at field capacity ($\text{m}^3 \text{m}^{-3}$), θ_{WPP} = water content at wilting point ($\text{m}^3 \text{m}^{-3}$), and Z_r = root zone depth (m).

The readily available water (RAW), which is the fraction of AW that a crop can deplete from the root zone without experiencing water stress, was estimated using equation 83 of FAO (equation 3.2) (Allen *et al.*, 1998).

$$RAW = pAW \dots\dots\dots \text{Equation 3. 2}$$

Where; RAW = readily available soil water in the plant root zone (mm), and p = average fraction of AW that can be extracted from the root zone before water stress (reduction in ETC) occurs. Its values range from 0 to 1 for various crops. The p average fraction of potato is 0.35.

This value was taken from table 83 of FAO 56 (Allen *et al.*, 1998). For accuracy purposes, samples were duplicated during the analyses.

For chemical analyses of the experimental soil, soil pH was determined in a 1:2.5 (w/v) H₂O extract. Total N was analyzed using the Kjeldahl digestion method (Okalebo *et al.*, 2002). In this method, the N is initially converted to ammonia (NH₃) using metal-catalyzed acid digestion (Motsara & Roy, 2008). The Mehlich double acid method was used to extract the soil elements such as phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn) and sodium (Na) (Mylavarapu *et al.*, 2002). Exchangeable Na and K were determined with a flame photometer using 589 and 766 nm wavelengths, respectively. Exchangeable Ca, Mg and Mn were measured with AAS (atomic absorption spectrophotometer) using wavelengths of 422.7, 285.2 and 279.2 nm, respectively. Available P was determined spectrophotometrically. Total organic carbon was determined using the colorimetric method following a spectrophotometer reading (Anderson & Ingram, 1993). Exchangeable acidity was measured at pH < 5.5 (Okalebo *et al.*, 2002). Available iron (Fe), zinc (Zn) and copper (Cu) were extracted in a 1:10 (w/v) ratio with 0.1 M HCL followed by AAS reading at the wavelength of 324.7, 248.3 and 213.9 nm, respectively (Githaiga *et al.*, 2020; Mehlich *et al.*, 1962). For the quality control of the analyses, samples were analyzed with the reference soil sample (with known values).

3.2.3 Water analysis

An aliquot of water for irrigation was taken for analysis at KALRO, Nairobi to check its suitability for irrigation. The pH and electrical conductivity (EC) of the sample were measured with a pH meter. Na and K concentrations were measured with a flame photometer using 589 and 766 nm wavelengths, respectively, while Ca and Mg were determined using AAS at wavelengths of 422.7 and 285.2 nm, respectively (Culkin & Cox, 1966). The chloride concentration of the water sample was determined by titrating an aliquot with silver nitrate and potassium dichromate, while carbonates were analyzed as bicarbonates by titrating the sample with hydrochloric acid and phenolphthalein (Culkin & Cox, 1966). The sulphate content of the sample was analyzed using the turbid metric method. The sodium absorption ratio was estimated using sodium, calcium and magnesium concentrations.

3.2.4 Potato Variety

Apical rooted cuttings of *Shangi* potato variety were used in this experiment, as it is mainly grown by farmers in the growing area (Janssens *et al.*, 2013). The variety is mostly

grown at an altitude above 1500 m (Nakuru, Bomet, Narok and Kericho). It is early maturing (≤ 3.5 months), high yielding and moderately susceptible to late blight (NPCK, 2019). Its tubers have oval-shaped smooth cream skin and medium to deep eyes, white when fresh. *Shangi* is a semi-erect medium-tall variety (slightly below 1 metre in height) with moderately strong stems and light green broad leaves. It flowers profusely, and the flowers are pink (NPCK, 2019). The crop requires a mean daily temperature range of 18–20 °C and less than 15 °C nighttime temperature, but it also performs well under 20–25 °C and below 20 °C for day and night temperatures, respectively (Kumar *et al.*, 2015).

3.2.5 Experimental procedure

The experimental site was under fallow for one year prior to the setting up of the experiment. It was under maize before the fallow period. Before planting, the land was ploughed to a depth of 0.3 m, after which plots were prepared by raising the soil to 0.4 m. Each experimental plot, measuring 9.45 m² (3.5 m × 2.7 m), was planted with 45 apical rooted cuttings of *Shangi* potato variety in five rows. Spacing of 0.3 m and 0.70 m between plants and rows, respectively, was used. This resulted in 47,617 apical rooted cuttings ha⁻¹. A randomized complete block design (RCBD) in a split-plot arrangement was used. The main plot treatments comprised two irrigation treatments: full supplemental irrigation (FI) and rain-fed potato production (RF) since irrigation requires a large plot. The sub plot treatments were four N rates; 0 (N0), 60 (N1), 90 (N2) and 130 kg N ha⁻¹ (N3). For FI treatment, irrigation was applied after the occurrence of rainfall once 40% of available water was depleted. Available water was monitored using time-domain reflectometry (TDR) moisture meter, and irrigation was applied based on daily crop evapotranspiration collected from the weather station of Egerton University. All plots were irrigated at the same level of water (during the first two weeks to encourage the crop establishment), but thereafter irrigation was daily scheduled (when there was no rain and 40% of available water was depleted) to deliver the calculated quantity of water based on daily crop evapotranspiration. N was applied in splits at 10 (40%), 30 (40%) and 50 (20%) days after planting. Urea fertilizer was used as a source of N in this study. Each treatment was replicated in three different blocks. The different blocks, main plots and subplots were separated by a 1.5 m buffer.

Lateral driplines that supply 1.6 L h⁻¹ spaced at 30 cm were placed in each row to supply water. During planting, 90 kg ha⁻¹ of potassium sulphate and 50 kg ha⁻¹ of triple superphosphate fertilizers were applied to each plot. To control the prevailing potato diseases (the early and late blight) and pests, Ridomil Gold MZ 68 WG (1 kg ha⁻¹) combined with

mancozeb (1 kg ha⁻¹) fungicides and VOLTAGE 5EC (350 ml ha⁻¹) were used, respectively. Weeding was manually done every three weeks, while earthing up was carried out one month after planting.

3.3 Data collection

3.3.1 Crop water demand

Reference crop evapotranspiration (ET₀) was estimated based on daily data collected from the weather station using Penman–Monteith’s equation (Allen *et al.*, 1998; Jensen & Allen, 2016).

$$ET_0 = \frac{\Delta(Rn-G) + \rho_a c_p \left(\frac{e_s - e_a}{r_a}\right)}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \dots\dots\dots \text{Equation 3. 3}$$

Where; ET₀ = reference crop evapotranspiration, Δ = slope of vapour saturation pressure, Rn = net radiation, G = soil heat flux; ρ_a = mean air density at the constant air pressure, c_p = specific heat of the air, e_s – e_a = vapour pressure deficit, γ = psychrometric constant, r_s = surface resistance and r_a = aerodynamic resistance.

The actual crop evapotranspiration (ET_c) was computed as the product of ET₀ and the crop coefficient (K_c).

$$ET_c = K_c \times ET_0 \dots\dots\dots \text{Equation 3. 4}$$

The crop coefficient at different crop stages was calculated using the formulae 59, 62 and 65 of FAO (Allen *et al.*, 1998). The average values of K_c at different crop stages were 1.14 and 1.18 for the initial stage, 0.75 and 0.78 for the growth stage, 1.12 and 1.14 for the middle stage, and 0.63 and 0.65 for the maturation stage for seasons one and two, respectively (Table 3.2). The equivalence period of different stages of potato corresponded to 25, 30, 30 and 30 days for initial, growth, middle and tuber maturity stages.

Soil moisture content was taken during the growing season. Cumulative actual potato evapotranspiration (ET_a) was estimated using a water balance equation (equation 3.5) (Sharma *et al.*, 2017a):

$$ET_a = P + I \pm \Delta s - R - D \dots\dots\dots \text{Equation 3. 5}$$

Where; P = amount of precipitation throughout the potato-growing season, I = total amount of additional irrigation supplied during the growing season of potato (mm), ΔS = change in soil water content in the root zone during the growing season of potato (mm), R = runoff loss (mm) and D = loss due to deep drainage during the growth period (mm). R is ignored since the slope of the experimental site is relatively small with adequate soil infiltration and irrigation was supplied through drip irrigation. Loss due to deep drainage (D) was expected to occur when

rainfall surpassed the soil water deficit (which was estimated as field capacity minus soil water content before a rain) in the root zone before precipitation. Irrigation never surpassed the soil water deficit level and thus was considered to cause no loss due to deep drainage.

Table 3.2: Monthly average of K_c , ET_0 and ET_c .

Months	Season 1				Season 2			
	Jul	Aug	Sep	Oct	Oct	Nov	Dec	Jan
K_c	1.14	0.75	1.12	0.63	1.18	0.78	1.14	0.65
ET_0 (mm)	3.49	3.57	4.2	4.3	3.08	3.08	4.32	4.5
ET_c (mm)	4.63	4.32	5.32	4.93	4.26	3.86	5.46	5.15

3.3.2 Yield components

Plant height, number of branches, biomass, number of tubers per plant, total tuber yield and marketable yield were collected as yield components from six plants in the central rows of each subplot. The harvest index (HI) was expressed as the percentage of tuber yield (Y) in the total biomass at harvest (Tbh) (aboveground biomass plus tuber yield at harvest) (equation 3.6).

$$HI = \frac{Y}{Tbh} \times 100 \dots \dots \dots \text{Equation 3. 6}$$

3.3.3 Water use efficiency and irrigation water use efficiency

Water use efficiency (WUE) and irrigation water use efficiency (IWUE) were computed using the following equations (Erdem *et al.*, 2006).

$$WUE = \frac{Y}{ET_a} \dots \dots \dots \text{Equation 3. 7}$$

$$IWUE = \frac{YI - YNI}{I} \dots \dots \dots \text{Equation 3. 8}$$

Where; YI = total tuber yield of an irrigated plot (kg ha^{-1}), YNI = total tuber yield of a non-irrigated plot (kg ha^{-1}) and I = amount of irrigation supplied during the growing season of potato (m^{-3}).

3.3.4 Nitrogen use efficiency

Nitrogen use efficiency (NUE) was computed using the following formula (Leal Filho *et al.*, 2015).

$$NUE = \frac{Tyfp - Tyufp}{q} \dots \dots \dots \text{Equation 3. 9}$$

Where; NUE is nitrogen use efficiency (kg kg^{-1}), Tyfp is the yield of the fertilized plot (kg), Tyufp is the yield of the unfertilized plot (kg) and Q is the amount of nutrient applied (kg).

3.4 Data analysis

Before analysis, data were subjected to the normality test at a probability level of 0.05 (Shapiro–Wilk test) in R software (version 3.6.3) (R-Core-Team, 2020) using the following equation. For any data that were not normally distributed, fitting data transformation was performed. Analysis of variance (ANOVA) was conducted using the following statistical model.

$$Y_{ijkl} = \mu + S_i + B(i)_j + I_k + SI_{ik} + BI(i)_{jk} + N_l + SN_{il} + IN_{kl} + SIN_{ikl} + \varepsilon_{ijklm} \quad \text{Equation 3. 10}$$

Where; μ = overall mean, S_i = effect of the i th season, $B(i)_j$ = effect of the j th block within the i th season, I_k = effect of the k th irrigation, SI_{ik} = interaction effect of the i th season and k th irrigation, $BI(i)_{jk}$ = error term of the main plots, N_l = effect of l th nitrogen rate, SN_{il} = interaction effect of the i th season and l th nitrogen rate, IN_{kl} = interaction effect of k th irrigation and l th nitrogen rate, SIN_{ikl} interaction effect of the i th season, k th irrigation and l th nitrogen rate and ε_{ijklm} = random error term for the subplots.

The least significant difference (LSD) test was used to separate the treatment means at a 0.05 significant level. Regression analyses were carried out at a 0.05 significant level to determine total tuber yield, WUE and NUE responses to N levels in a mollic Andosol. The Pearson correlation coefficient was computed at a probability level of 0.05 to test the significance of the relationship between tuber number per plant, WUE and NUE values as well as total tuber yield. During the analysis, outlier data were identified using the control chart technique (Bakar *et al.*, 2006). Any outlier data and not due to the treatment effect were deleted from the model and replaced by the nearest after confirming data entry error.

3.5 Results and discussion

3.5.1 Physico-chemical properties of experimental soil

The experimental soils had a sandy loam texture comprising 60.65% sand, 28.2% silt, and 11.15% clay (Table 3.3). The average soil moisture content at FC from the surface layer down to 0.45 m depth was on average 20.1%, and the PWP of the corresponding depth was on average 12.05% (Table 3.3). The experimental soil had a medium acidic pH and organic carbon content. The available total N of the experimental soil before planting was, on average, 0.15%,

classified as low (Table 3.4). The irrigation water used had a medium salinity level and high sulphate (Table 3.5). This indicated that the quality of water used for this study was suitable for irrigation. This interpretation was based on the USDA classification of irrigation water (Bauder *et al.*, 2011; Scherer *et al.*, 1996; Wilcox, 1955).

Table 3.3: Physical properties of the experimental soils

Depth (m)	Soil texture				Moisture retention %				Bulk density (g cm ⁻³)
	Sand %	Silt %	Clay %	Class	FC	PWP	AW	RAW	
0–0.15	63.7	26.2	10.1	SL	19.9	12.3	7.6	2.66	1.26
0.15–0.45	57.6	30.2	12.2	SL	20.3	11.8	8.5	2.98	1.34

SL = sandy loam, FC = field capacity, PWP = permanent wilting point, AW = total available water, RAW = readily available water of potato.

Table 3.4: Chemical properties of the experimental soils.

Soil depth	0–0.15 m		0.15–0.45 m	
	Value	Class	Value	Class
Soil pH	5.43	Medium acid	5.46	Medium acid
Exchange acidity mmol L ⁻¹	0.20	Adequate	0.21	Adequate
Total nitrogen (N) %	0.16	Low	0.14	Low
Total organic carbon %	1.69	Moderate	1.61	Moderate
Available P mg kg ⁻¹	21	Low	19.1	Low
K mmol L ⁻¹	1.14	Adequate	1.11	Adequate
Ca mmol L ⁻¹	5.6	Adequate	5.4	Adequate
Mg mmol L ⁻¹	1.61	Adequate	1.43	Adequate
Mn mmol L ⁻¹	1.37	Adequate	1.25	Adequate
Cu mg kg ⁻¹	1.80	Adequate	1.71	Adequate
Fe mg kg ⁻¹	12.2	Adequate	12.2	Adequate
Zn mg kg ⁻¹	2.45	Low	2.42	Low
Na mmol L ⁻¹	0.18	Adequate	0.17	Adequate

Table 3. 5: Composition of irrigation water used.

Parameters	Values
pH	8.09
Conductivity (EC) mS cm ⁻¹	0.27
Na mmol L ⁻¹	0.37
K mmol L ⁻¹	0.12
Ca mmol L ⁻¹	0.04
Mg mmol L ⁻¹	0.05
Carbonates (mmol L ⁻¹)	ND*
Bicarbonates (mmol L ⁻¹)	0.75
Chlorides (mmol L ⁻¹)	1.92
Sulphates (mmol L ⁻¹)	49.9
Sodium adsorption ratio	1.74

ND* = not detected.

3.5.2 Crop water demand and Crop evapotranspiration

During the first two weeks, 6.4 and 4.2 mm of water were supplied at the beginning of the first and the second seasons, respectively, to encourage plant root establishment. The cumulative actual crop evapotranspiration (ET_a) was 268.09 and 237.7 mm for RF and 359.47 and 381.89 mm for FI during the first and second growing seasons. This showed that the crop water demand was higher during the second season. This agreed with the previous studies that reported that the total seasonal potato ET_a varied from 350 to 800 mm for various climates and environments (Adavi *et al.*, 2018; Afzaal *et al.*, 2020; Ati *et al.*, 2012; Ati *et al.*, 2010; Djaman *et al.*, 2021; Ierna & Mauromicale, 2018; Meligy *et al.*, 2020; Nowacki, 2018; Paredes *et al.*, 2018). The supplemental irrigation applied was 91.38 and 144.19 mm for seasons one and two, respectively. This indicated a reduction in seasonal rainfall patterns due to low and erratic rainfall and high temperatures recorded during the second season. Muthoni *et al.* (2017) and Waaswa *et al.* (2021) reported a significant reduction in in-season rainfall followed by an uneven rainfall distribution in Nakuru County, Kenya. This demonstrated the need for supplemental irrigation in the potato-growing area of Nakuru county.

3.5.3 Plant growth

The effects of supplemental irrigation and N-fertilization on plant height and the number of branches per plant are presented in Tables 3.6 and 3.7. The results showed that plant height and number of branches per plant of potato were not significantly affected by the interaction effects of the two factors ($P > 0.05$). The average plant height in FI was significantly higher than in RF during the two growing seasons. This is in line with the previous research that reported that potato crop height increases with the amount of irrigation water applied (Farrag *et al.*, 2016; Metwaly & El-Shatoury, 2017; Zhang *et al.*, 2017b). This result contradicted the findings of Darabad (2014), who reported that potato plant height did not increase with irrigation amount. This difference in outcome can be attributed to the potato variety used in this study. Moreover, a significant increase in plant height and number of branches per plant was observed as the amount of applied N increased ($P < 0.001$). The highest plant height, 76.82 cm, was recorded under N3. This increase in plant height with N dosage was also reported in previous research (Godebo & Belay, 2020; Setu & Mitiku, 2020; Tolessa *et al.*, 2017). Sebnie *et al.* (2021) indicated that an application of mineral N fertilizer increased potato plant height compared to unfertilized plots. It was also observed that season did not affect plant height significantly. The difference in the average plant heights across seasons was not significant.

3.5.4 Yield components

The effects of supplemental irrigation and N-fertilization on yield components (tuber number per plant, total tuber yield, marketable yield and HI) during the growing seasons are presented in Tables 3.6 and 3.7. The results indicated that irrigation, N-fertilization and irrigation×nitrogen exhibited a significant effect on tuber number per plant, total tuber yield and marketable yield of potato. Conversely, HI was only significantly affected by N-fertilization ($P < 0.001$). It was also observed that the yield components except for HI statistically varied across the growing seasons. The FI significantly increased tuber number per plant, tuber yield and marketable yield compared to RF, regardless of N-fertilization. For different irrigation treatments, the tuber number per plant, total tuber yield and marketable yield ranged from 16 to 20, 20.86 to 44.11 t ha⁻¹, and 15.23 to 38.83 t ha⁻¹, respectively. The tuber yield and marketable yield were higher during the second growing season. This increase in potato yield in the second season can be attributed to the high ET_a recorded during the season. This is in line with the previous research that reported that potato is very susceptible or sensitive to water stress compared to many other crops. Full irrigation without water deficit throughout

the potato cycle always leads to a high yield (Darabad, 2014; Mattar *et al.*, 2021). Tuber initiation to maturity growth period forms the critical water-demand period where water deficits negatively affect potato productivity (Ahmadi *et al.*, 2010; Salter & Goode, 1967; Sasani *et al.*, 2006). Begum *et al.* (2018) found that a stable potato yield of 40–50 t ha⁻¹ or more can be achieved if the shortage of readily available water in the soil is eliminated. Previous studies found an increase in tuber number per plant and marketable potato yield of irrigated potato compared to rain-fed production (Abu El-Fotoh *et al.*, 2019; Djaman *et al.*, 2021; Waqas *et al.*, 2021). Djaman *et al.* (2021) also reported the highest tuber number per plant under full irrigation.

The tuber number per plant, tuber yield and marketable yield across N-fertilization varied from 13 to 23, 22.75 to 45.06 t ha⁻¹, and 16.12 to 39.84 t ha⁻¹, respectively. The highest tuber number per plant, tuber yield and marketable yield were observed with N3. Earlier works found that potato yield, regardless of irrigation, statistically increases with an increase in N rate up to 280 kg N ha⁻¹, then tended to increase faintly as N dosage increases further (Badr *et al.*, 2012; Ospina *et al.*, 2014; Shunka *et al.*, 2017). Further research needs to be conducted to determine the optimal nitrogen level for potato production in a mollic Andosol since this study did not find the point at which an increase in N dosage might decrease potato yield.

For irrigation×nitrogen effects, the highest tuber number per plant, 27, was obtained in FI with N3 treatment during the first season, while the lowest value, 11, was found under RF with N0 during the second growing season (Fig. 3.2 a and b). A significant increase in the total yield and marketable yield of all N treatments under FI compared to RF was also observed. Besides, the highest total tuber yield, 62.12 t ha⁻¹, and marketable yield, 55.79 t ha⁻¹, were found in FI with N3 during the second season, whereas the smallest total tuber yield, 15.21 t ha⁻¹, and marketable yield, 9.99 t ha⁻¹, were found under RF with N0 during the second season and the first season, respectively (Fig. 3.2 c, d, e, and f). It was also found that FI enhanced marketable tuber yield by 129.84, 94.63, 151.21 and 126.63% for N0, N1, N2 and N3, respectively, compared to rain-fed N-fertilization. A significant effect of irrigation×nitrogen on tuber yield was reported by Badr *et al.* (2012) in Egypt and (Tolessa, 2019) in Ethiopia.

An increment of HI with N level was found with the maximum value of HI, 54.69%, recorded in N3. However, the HI obtained with N3 did not differ significantly from the HI observed with N2. It was also found that supplemental irrigation did not affect HI. This disagreed with the earlier studies that reported a significant effect of irrigation for HI of potato with a reduction in HI as water stress becomes more severe (Ruttanaprasert *et al.*, 2016; Sobhani & Hamidi, 2015). This could be explained by the fact that the water deficit under RF

was not so severe as to affect HI during the growing seasons. To achieve an optimum marketable yield of potato grown on mollic Andosols of Kenya, supplemental irrigation with 130 kg N ha⁻¹ is required.

Table 3.6: Means separation of plant height, number of branches per plant and HI under different irrigation and N treatments

Treatments	Plant height (cm)	Number of branches per plant	HI (%)
Irrigation effect			
FI	72.58a	19a	56.29
RF	63.85b	15b	45.41
LSD	9.08	2.52	ns
Nitrogen effect			
N3	76.82a	19a	54.69a
N2	69.35b	18a	51.69ab
N1	67.36b	17a	49.12b
N0	59.35c	14b	47.91b
LSD	5.51	2.27	5.29

ns = not significant, alpha = 0.05. Same letters in the same column indicate no significant difference, while different letters indicate a significant difference at a significant level of 0.05.

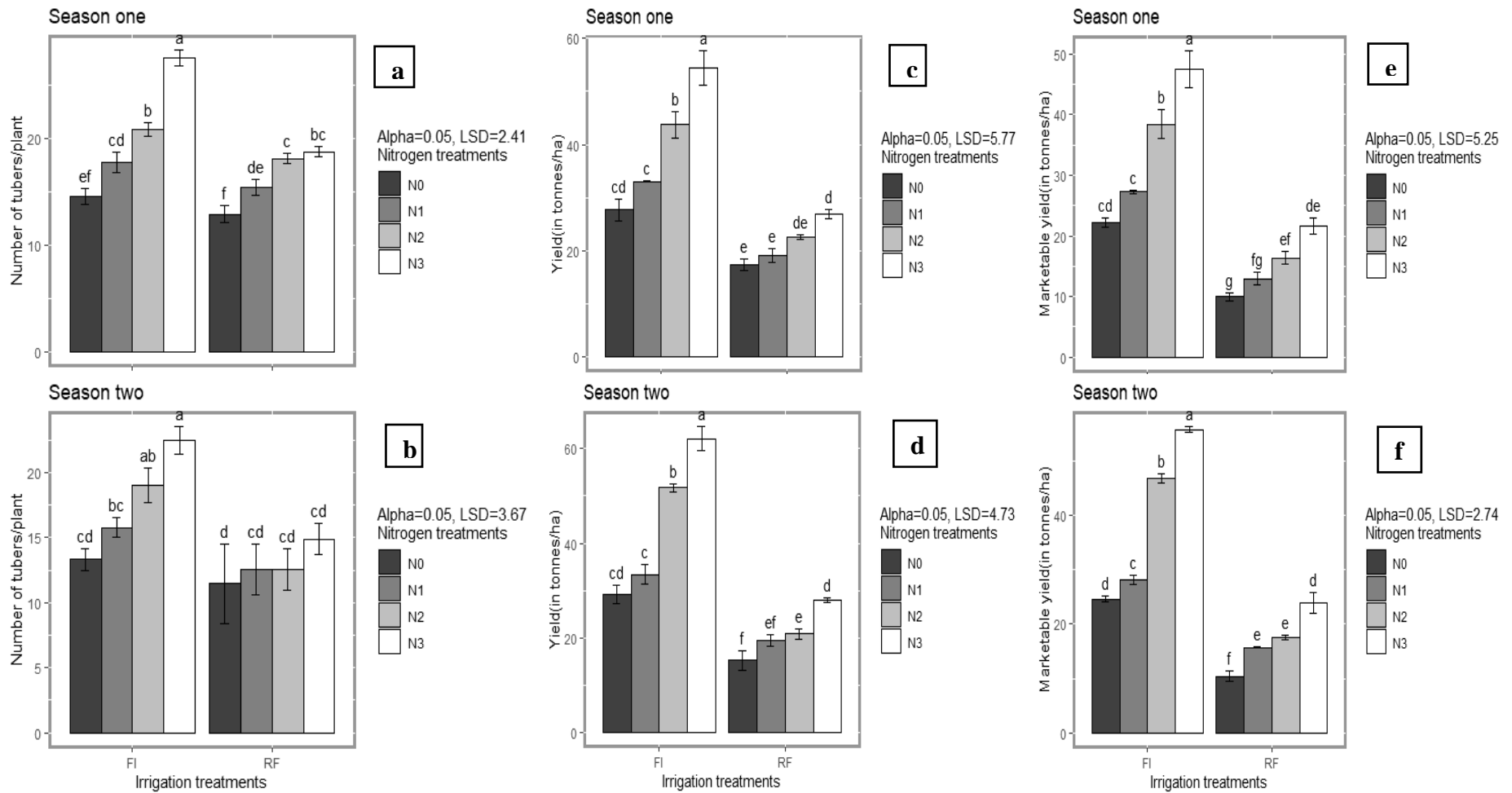


Figure 3.2: Means separation of tuber number per plant, total tuber yield and marketable tuber yield under different irrigation and N treatments of different growing seasons. Same letters indicate that there is no significant difference while different letters indicate there is a significant difference at a significant level of 0.05.

Table 3.7: Mean squares of plant height, branch number per plant, tuber number per plant, yield, HI and marketable yield under different irrigation and N treatments

Source of variation	df	Plant height	Number of branches per plant	Tuber number per plant	Total tuber yield	Marketable yield	HI
Season	1	226.03*	455.53*	107.97*	42.85*	131.51***	268.95
Replicate(season)	4	140.23	41.75	10.04	11.09	4.45	36.49
Irrigation	1	914.73	6.89	225.38**	5172.77***	4942.85***	1422.02
Season×irrigation	1	349.27	6.40	2.36	74.13*	33.05**	96.84
Replicate×irrigation(season) (Ea)	4	68.74	23.36	9.85	5.36	1.51	120.93
Nitrogen	3	618.76***	44.86***	134.62***	1005.90***	993.63***	108.54*
Season×nitrogen	3	82.60	5.85	5.86	14.84	12.15	42.28
Irrigation×nitrogen	3	54.47	17.84	23.72***	249.89***	200.95***	49.91
Season×irrigation×nitrogen	3	100.07	4.39	3.16	12.83	13.11	27.89
Error (Eb)	24	28.22	5.47	3.05	9.11	5.56	28.82
R ²		0.88	0.88	0.93	0.98	0.99	0.82
CVa		12.15	28.26	18.74	7.34	4.69	21.63
CVb		7.79	13.68	10.43	9.57	9.00	10.56

HI = harvest index, Ea = error of the main plots, Ea = error of the subplots, CVa = coefficient of variation for the main plots, CVb = coefficient of variation for the subplots. ‘***’, ‘**’ and ‘*’ are significance codes at 0.001, 0.01 and 0.05, respectively.

3.5.5 Water use efficiency (WUE) and irrigation water use efficiency (IWUE)

Data collected on potato WUE and IWUE for all treatments are presented in Table 3.8. It was found that irrigation and irrigation×nitrogen did not interact with WUE. However, N-fertilization statistically increased the WUE of potato. N-fertilization N3 produced higher potato WUE (14.24 kg m⁻³), followed by N2 (11.69 kg m⁻³), N1 (9.64 kg m⁻³) and N0 (7.47 kg m⁻³) (Fig. 4a and b). Previous studies found an increase in potato WUE with an increase in N rate (Badr *et al.*, 2012; Tolessa, 2019). IWUE indicates how the crop used the additional applied water in different N-treatments. It was observed that N-fertilization considerably ($P < 0.001$) interacted with potato IWUE in a mollic Andosol. IWUE obtained with N-fertilizations N3 and N2 were high but did not differ from each other. The lowest IWUE, 10.10 kg m⁻³, was recorded with N0 (Fig. 3.3 c and d). This indicated that the additional water applied was more significantly used when applying N3 and N2 than N1 and N0.

Table 3.8: Means squares of WUE and IWUE under different irrigation and N treatments

Source of variation	df	WUE	Source of variation	df	IWUE
Season	1	23.41*	Season	1	100.21*
Replicate(season)	4	4.36	Replicate(season)	4	8.66
Irrigation	1	48.72	Nitrogen	3	386.72***
Season×irrigation	1	48.04	Season×nitrogen	3	5.63
Replicate×irrigation(season) (Ea)	4	1.67	Error	12	20.45
Nitrogen	3	100.20***	R2		0.84
Season×nitrogen	3	0.60	CV		25.18
Irrigation×nitrogen	3	2.16			
Season×irrigation×nitrogen	3	4.76			
Error (Eb)	24	1.12			
R2		0.95			
CVa		12.01			
CVb		9.83			

Ea = error of the main plots, Ea = error of the subplots, CVa = coefficient of variation for the main plots, CVb = coefficient of variation for the subplots. ‘***’, ‘**’ and ‘*’ are significance codes at 0.001, 0.01 and 0.05, respectively.

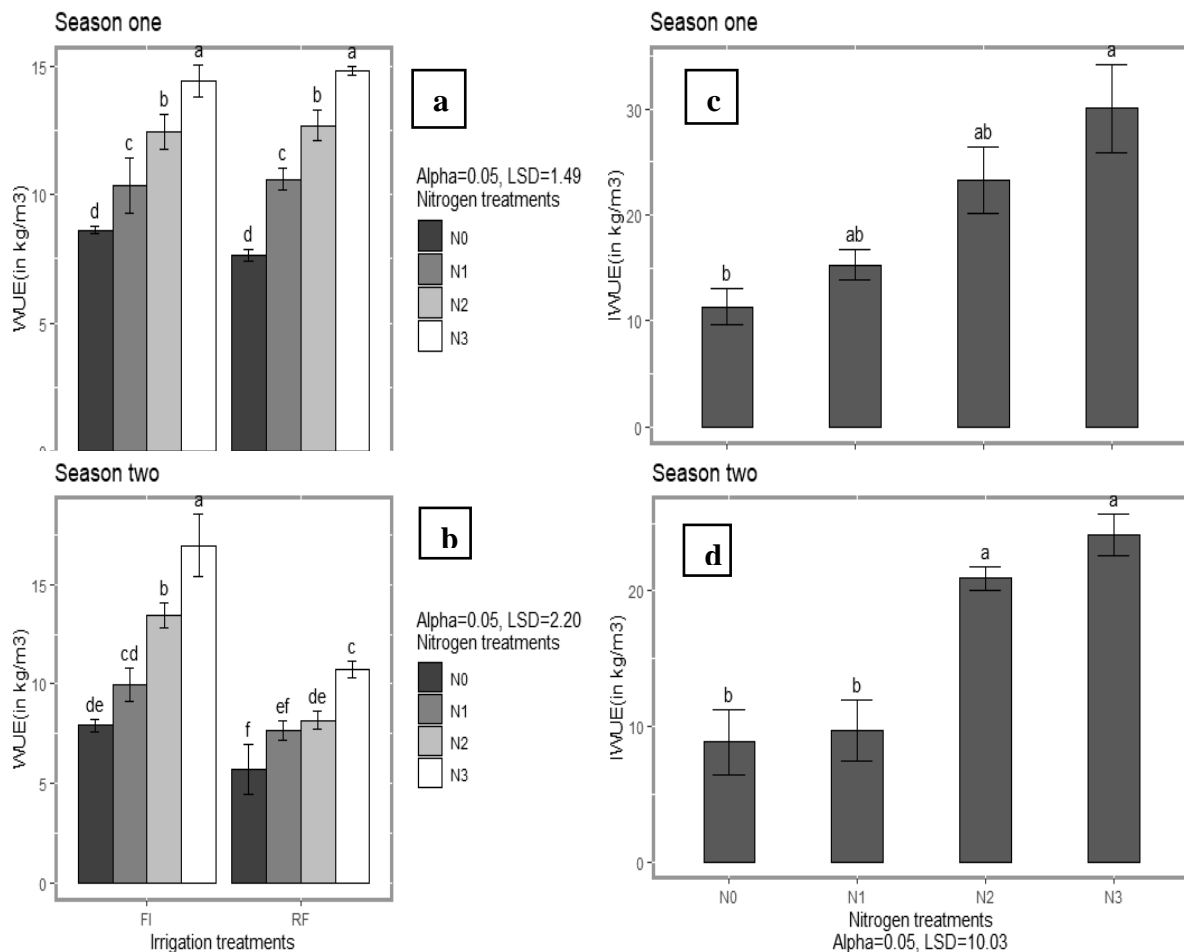


Figure 3.3: Means separation for WUE and IWUE under different irrigation and N treatments of different growing seasons. Same letters indicate that there is no significant difference while different letters indicate there is a significant difference at a significant level

3.5.6 Nitrogen use efficiency

Irrigation ($P < 0.05$), N-fertilization ($P < 0.001$) and irrigation \times nitrogen ($P < 0.001$) exhibited a significant effect on NUE (Table 3.9). The maximum potato NUE, 197.22 kg kg⁻¹ N, was observed under FI. It was observed that the NUE of potato increased as the N level increased, with the maximum NUE obtained with N3, but it was not significantly different from potato NUE found with N2. The smallest NUE was obtained with N1. On the contrary, Banerjee *et al.* (2015) found that NUE decreased with an increase in N rate. For irrigation \times nitrogen effects for NUE, a significant increase of potato NUE under FI was observed during the two seasons compared to RF with the maximum NUE, 236.44 kg kg⁻¹ N, obtained under FI with N3, but not significantly different from the NUE of potato obtained under FI with N2 (Fig. 3.4 a and b). This implied that for an improvement of NUE in potato grown in a mollic Andosol, the amount of water and N dosage should be applied at their

optimum levels. The optimum level of NUE in a mollic Andosol can be achieved with 90 kg N ha⁻¹ since the NUE obtained with 130 kg N ha⁻¹ did not differ from NUE found with 90 kg N ha⁻¹.

Table 3.9: Mean squares of NUE under different irrigation and N treatments

Source of variation	df	NUE
Season	1	5709.06
Replicate(season)	4	752.66
Irrigation	1	139578.21***
Season×irrigation	1	604.59*
Replicate×irrigation(season) (Ea)	4	1229.02
Nitrogen	2	17466.55***
Season×nitrogen	2	153.87
Irrigation×nitrogen	2	6650.22
Season×irrigation×nitrogen	2	256.36
Error (Eb)	16	224.72
R ²		0.98
CVa		25.98
CVb		11.11

Ea = error of the main plots, Ea = error of the subplots, CVa = coefficient of variation for the main plots, CVb = coefficient of variation for the subplots. ‘***’, ‘**’ and ‘*’ are significance codes at 0.001, 0.01 and 0.05, respectively.

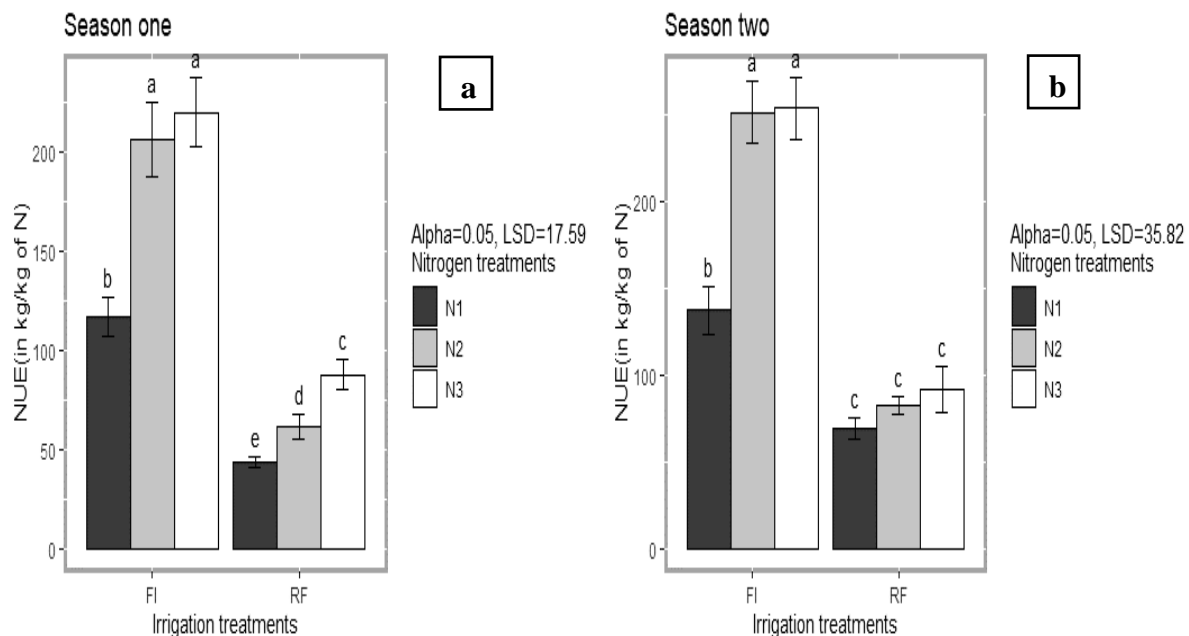


Figure 3.4: Means separation for WUE and IWUE under different irrigation and N treatments of different growing seasons. Same letters indicate that there is no significant difference while different letters indicate there is a significant difference at a significant level of 0.05.

3.5.7 Relationship between potato yield, WUE, NUE and N rate under different irrigation treatments

The production functions of tuber yield, WUE and NUE were evaluated for different irrigation treatments to show their responses to N level in a mollic Andosol (Fig. 3.5 a, b and 3.6). As expected, the relationships between tuber yield, WUE and NUE and N applied were linear (all F-values were significant at $P < 0.05$). The regression equations and determination coefficients between N-fertilization and tuber yield obtained were the following.

$$\text{FI: } Y = 0.2368X + 25.343, R^2 = 0.90 \dots\dots\dots \text{Equation 3. 11}$$

$$\text{RF: } Y = 0.0835X + 15.313, R^2 = 0.92 \dots\dots\dots \text{Equation 3. 12}$$

These equations indicated that total potato tuber yield increased by about 236 and 83 kg ha^{-1} for each kg of N applied under FI and RF, respectively. This showed that an increase in a unit of N greatly increased total potato tuber yield under FI compared to RF. The following regression equations and determination coefficients were obtained between WUE and N-fertilization.

$$\text{FI: } Y = 0.0578X + 7.7192, R^2 = 0.95 \dots\dots\dots \text{Equation 3. 13}$$

$$\text{RF: } Y = 0.0464X + 6.5086, R^2 = 0.99 \dots\dots\dots \text{Equation 3. 14}$$

This indicated that an increment of each kg of N applied respectively in FI and RF increased the WUE of potato by approximately 0.06 and 0.05 kg m⁻³. The highest slope of the regression between WUE vs N-fertilization corresponded to FI. For NUE and N-fertilization, the following equations and determination coefficients were also evaluated.

$$\text{FI: } Y = 1.4931X + 57.868, R^2 = 0.73 \dots\dots\dots \text{Equation 3. 15}$$

$$\text{RF: } Y = 0.4753X + 28.325, R^2 = 0.99 \dots\dots\dots \text{Equation 3. 16}$$

The slopes of this equation showed that an increase of each kg of N applied enhanced the NUE of potato by approximately 1.49 and 0.47 kg kg⁻¹ N under FI and RF, respectively. These results demonstrated the importance of supplemental irrigation in the growing area for a high NUE of potato. It was found that tuber yield was positively correlated with both NUE ($r = 0.95^{***}$) and WUE ($r = 0.72^{***}$) (Fig. 3.7). The total tuber yield was also positively correlated with the tuber number per plant ($r = 0.75^{***}$). This showed that the increase in total tuber yield observed in this study depended on the tuber number per plant. On the contrary, a previous study reported that there was no correlation between tuber number per plant and potato yield (Badr *et al.*, 2012). This difference can be attributed to the potato variety used as plant material as well as the soil type.

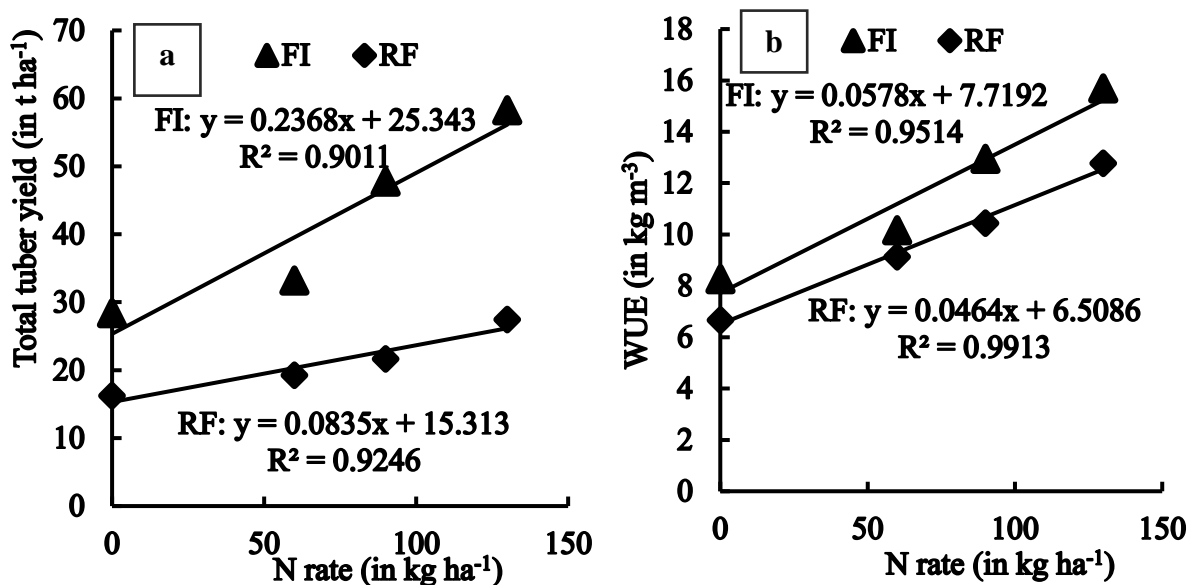


Figure 3.5: Relationship between total tuber yield, and WUE and N rates under different irrigation treatments

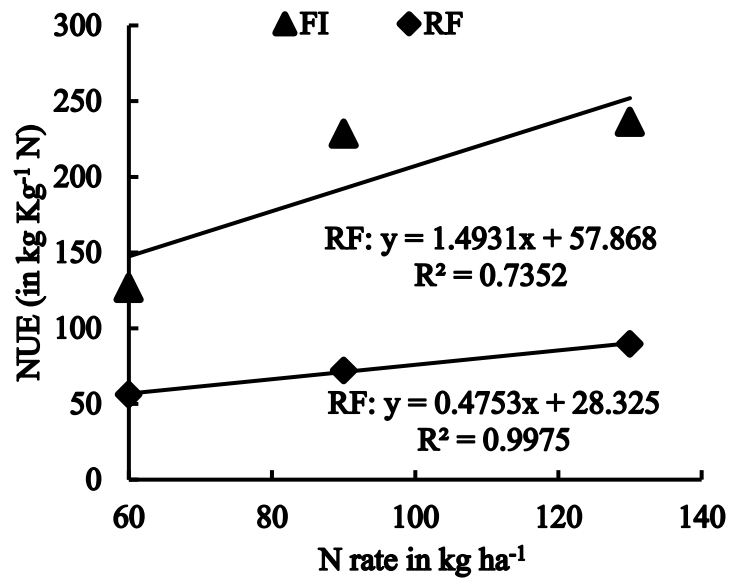


Figure 3.7: Relationship between NUE and N rates under different irrigation treatments

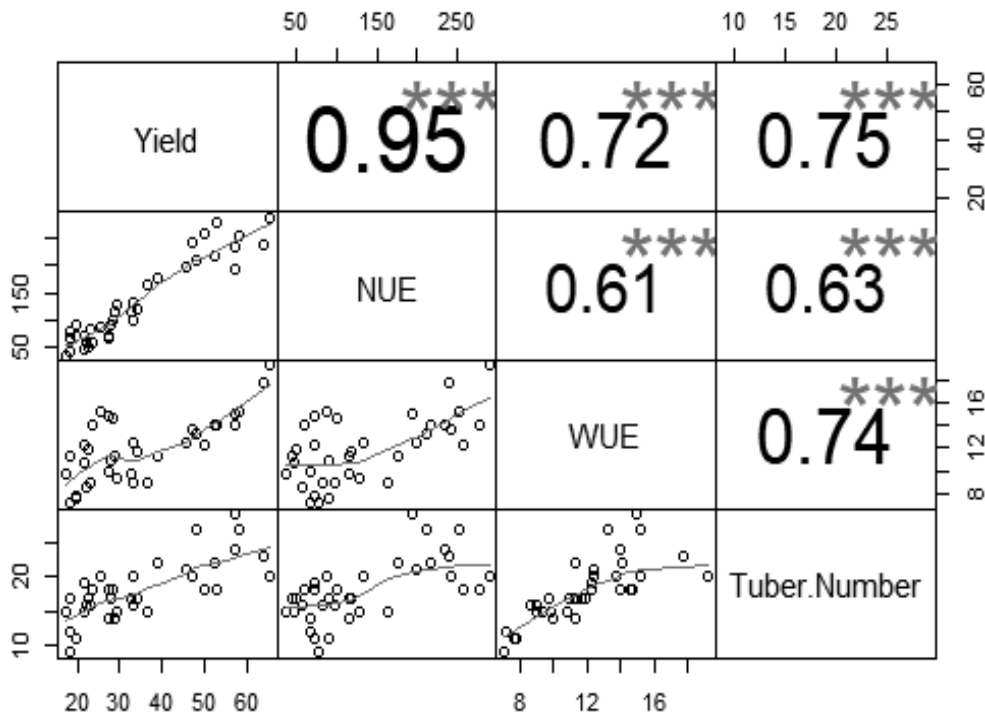


Figure 3.6: Correlation between the number of tubers per plant, tuber yield, WUE and NUE.

3.6 Conclusion

Yield components of potato are largely more responsive to the interaction effect of irrigation×nitrogen than a single effect of irrigation and N-fertilization. The highest total tuber yield and marketable yield were obtained under FI with an application of 130 kg N ha⁻¹. In this study, WUE was high when applying 130 kg N ha⁻¹. The NUE consistently increased with the

increase in N rate up to 90 kg N ha⁻¹ in the two irrigation treatments. There is a high positive correlation between tuber number per plant, tuber yield, WUE and NUE. This study highlights the importance of introducing supplemental irrigation in the potato producing area in Kenya. Farmers can achieve a high potato yield and marketable tuber yield in a mollic Andosol when water deficits of the growing season are eliminated with supplemental irrigation and an application of 130 kg N ha⁻¹.

CHAPTER FOUR

EFFECT OF NITROGEN AND IRRIGATION REGIMES ON GROWTH AND YIELD OF POTATO GROWN IN A MOLLIC ANDOSOL

Abstract

Water and nitrogen (N) are some important factors influencing potato (*Solanum tuberosum* L.) production, and the response of potato to these factors can vary with soil types and potato varieties. The objective of this study was to determine the effect of nitrogen rates and irrigation regimes on the growth and yield of apical rooted cuttings of *Shangi* potato variety grown in a mollic Andosol in Kenya. A randomized complete block design (RCBD) in a split-plot arrangement was used. The main plot treatments comprised four irrigation regimes of ETC100%, ETC85%, ETC75% and ETC50%, where ETC100% was irrigated according to the soil water depletion 2 days after full irrigation. The subplot treatments were four N rates: 0 (N0), 60 (N1) (60), 90 (N2) and 130 kg N ha⁻¹ (N3). The results showed that the cumulative actual crop evapotranspiration (ETa) in a mollic Andosol was on average 2001.4, 302.1, 342.4 and 402.8 mm under ETC50%, ETC75%, ETC85% and ETC100%, respectively. N had a significant ($P < 0.001$) effect on potato height and number of branches per plant, where the highest potato height, 92.67 cm, and number of branches per plant, 17, were observed with 130 kg N ha⁻¹. Potato grown under full irrigation (ETC100%) with an application of 130 kg N ha⁻¹ produced the highest potato tuber yield, 58.28 t ha⁻¹, and marketable tuber yield, 54.21 t ha⁻¹. Potato tuber number per plant significantly reduced with a decrease in N dosage, and the maximum number, 23, was obtained when 130 kg N ha⁻¹ was applied. The Pearson correlation indicated a significant correlation ($r = 0.7***$) between total tuber yield and tuber number per plant. The maximum harvest index (HI), 57.12%, was obtained under ETC50% with 130 kg N ha⁻¹, whereas the highest dry matter of potato tubers, 30%, was observed under 130 kg N ha⁻¹. To achieve a high yield of potato in a mollic Andosol, this study recommends an irrigation regime of ETC100% with an application of 130 kg N ha⁻¹ in three split applications at 10 (40%), 30 (40%) and 50 (20%) days after planting.

Keywords: Irrigation, Harvest index, mollic Andosols, Nitrogen, Yield

4.1 Introduction

Potato (*Solanum tuberosum* L.) is the world's third major food crop after rice (*Oryza sativa*) and wheat (*Triticum aestivum*) (Campos & Ortiz, 2020). Its production is estimated at 388 million tonnes on 19.3 million hectares globally. Asia and Europe produce about 81.17% of the world's production (FAOSTAT, 2019). There has been an impressive increase in East

African potato production in recent years, indicating its significant contribution to local food systems (Campos & Ortiz, 2020; FAOSTAT, 2019). It has been included in the national priority list of crops in East Africa owing to its role in national food security (FAOSTAT, 2020). Due to a reduction in seasonal rainfall alongside soil N deficiency, the water shortage has lowered potato yield in Kenya (Muthoni *et al.*, 2021). Potato is susceptible to water stress compared to several crops, and full irrigation throughout the potato cycle always leads to a high yield (Darabad, 2014; Mattar *et al.*, 2021). It needs about 25–50 mm of water per week, leading to potato response with an increase in yield up to 2 t ha⁻¹ for each 20 mm of applied water (Asfary *et al.*, 1983; Fabeiro *et al.*, 2001). The total seasonal potato ET_a was estimated at 350 to 800 mm depending on the soil type, irrigation management, cultivar, climates, field and environmental conditions (Adavi *et al.*, 2018; Afzaal *et al.*, 2020; Ati *et al.*, 2012; Ati *et al.*, 2010; Djaman *et al.*, 2021; Ierna & Mauromicale, 2018; Meligy *et al.*, 2020; Nowacki, 2018; Paredes *et al.*, 2018).

High productivity of potato is obtained when soil moisture is kept consistently at an optimum level with N availability during the critical demand period (Badr *et al.*, 2012). Most of the soils in potato-growing areas in Kenya are deficient in N. The application of mineral N fertilizer is therefore essential (Ayyub *et al.*, 2019). The soils are classified as mollic Andosols and exhibit high infiltration rates (Hoyos & Comerford, 2005; Jiménez *et al.*, 2006). Optimization of both irrigation water and N application is critical for improving potato yields and minimizing the risk of N percolating to the underground water table (Badr *et al.*, 2012; Djidonou *et al.*, 2013; El Mokh *et al.*, 2015; Fouda *et al.*, 2012; Gao *et al.*, 2014; Tolessa, 2019). This is also in view of high fertilizer costs and the shortage of irrigation water.

The effect of both N and irrigation on potato production and quality is frequently reported in the literature but with different conclusions and recommendations. This is because the optimal N levels differ for different potato cultivars, soil types and environmental conditions (Badr *et al.*, 2012; Bélanger *et al.*, 2000). So far, no study has reported the management of these inputs in potato production in a mollic Andosol, especially in Kenya. This becomes a great challenge for farmers producing potato in a mollic Andosol which is vulnerable to water infiltration and loss of soluble elements. Therefore, the objective of this study was to determine the effect of N rates and irrigation regimes on the growth and yield of potato grown in a mollic Andosol in Kenya.

4.2 Materials and methods

4.2.1 Experimental site

A two-season experiment was conducted under two different rain shelters between July 2020 and March 2021 at Agro-Science Park field, Egerton University (0.3031° S, 36.0800° E), Kenya. The experimental site is located in agro-ecological zone III at an altitude of 2670 m above sea level. The soils at the experimental site are classified as mollic Andosols (Jaetzold *et al.*, 2007).

4.2.2 Variety

Apical rooted cuttings of *Shangi* potato variety (NPCK, 2019) were used, which was the same variety used in the experiment of chapter three.

4.2.3 Experimental procedure (Rain shelter experiment)

Rain shelters with dimensions of 14 m × 20 m were put into place in each growing season. The four sides of the structure were opened during the daytime to allow air inflow and closed at night. The minimum and maximum temperatures in the rain shelters were 12 and 22.1 and 15.5 and 27.3 °C for the first and the second seasons, respectively. Land preparation was carried out by ploughing the soil at 0.3 m depth, after which plots were prepared by raising the soil to approximately 0.4 m. The apical rooted cuttings of 7 cm of height were sourced from Stokman Rozen Company located in Naivasha, Kenya. Each experimental unit 1 m × 2.5 m (2.5 m²) received 9 rooted cuttings (leading to 47,617 apical rooted cuttings ha⁻¹) of the *Shangi* potato variety. They were planted at a spacing of 0.30 m × 0.70 m (between rows and lines, respectively) in a set of three rows. A randomized complete block design (RCBD) with a split-plot arrangement was used. The main plot treatments comprised four irrigation regimes: ETC100%, ETC85%, ETC75% and ETC50%, where ETC100% was irrigated according to the soil water depletion 2 days after full irrigation. The subplot treatments were four N rates: 0 (N0), 60 (N1), 90 (N2) and 130 kg N ha⁻¹ (N3). Lateral driplines that supply 1.6 L h⁻¹ inline dripper spaced at 30 cm were placed in each row. Irrigation water was supplied by drip irrigation, with each plot receiving the same level of water during the two first weeks. According to the water regime allocated, the drip irrigation was then automatized in minutes for each main plot after the two first weeks. The soil moisture content was monitored with time-domain reflectometry (TDR) moisture meter. Nitrogen was applied in splits at 10 (40%), 30 (40%) and 50 (20%) days after planting. Urea fertilizer was used as a source of N. During planting, 90 kg ha⁻¹ of potassium sulphate and 50 kg ha⁻¹ of triple superphosphate fertilizers

were applied to each plot. Each treatment was replicated in three different blocks. Each block was separated by 1.5 m to avoid irrigation leaching effects. The experimental units within the blocks were also separated by 1.5 m. To control the prevailing potato diseases (the early and late blight) and pests, Ridomil Gold MZ 68 WG (1 kg ha⁻¹) combined with mancozeb (1 kg ha⁻¹) fungicides and VOLTAGE 5EC (350 ml ha⁻¹) were used, respectively. Weeding was manually done every three weeks, while earthing up was carried out one month after planting.

4.3 Data collection

Data were collected on crop water demand, potato plant height, number of branches, total biomass, tuber dry matter (DM), tuber number per plant, tuber yield and harvest index.

4.3.1 Estimation of crop water demand

For crop water demand, the soil moisture content was taken before and after each irrigation every 2 days within soil depths of 0.3 m from planting till harvest using time-domain reflectometry (TDR) soil moisture meter. The difference in moisture values within 2 days from each plot was obtained as volumetric water content (θ). The equivalent water depth (De) of plant-available water (m⁻³) associated with this change was determined using the equation of Marshall *et al.* (1996) (equation 4.1). Crop evapotranspiration was determined using the water balance equation (equation 3.5) (Sharma *et al.*, 2017a). Since the experiment was conducted in a rain shelter and the water was supplied using drip irrigation, P, D and R were assumed to be negligible. Therefore, equation 12 was summarized as equation 4.2.

$$De = \theta \times Zr \dots\dots\dots \text{Equation 4. 1}$$

$$ETa = I \pm \Delta s \dots\dots\dots \text{Equation 4. 2}$$

4.3.2 Growth and yields data

Plant height (in cm) and the number of primary branches per plant were taken every two weeks on five tagged plants per subplot from 14 days after planting (DAP) until harvest. The plant height and the number of branches per plant used in this study were collected at DAP66 since the N was applied in splits. Five plants were randomly chosen and removed with the tuber from each subplot at harvest. The aboveground biomass and the tuber sample from each subplot were weighed separately using an electronic balance. The sum of their weight was recorded as total biomass at harvest. The tuber number per plant was counted and classified in four different sizes (chats: tuber size < 25 mm, C1: 26 mm < tuber size < 45 mm, C2: 46 mm

< tuber size < 60 mm and ware: tuber size > 61 mm in diameter). The fresh tuber yield was separated into three categories (total fresh, unmarketable and marketable tuber yield). The total yield was measured by taking the total tuber weight per plant. The unmarketable yield was taken as the weight of the chats since they are not marketable. The marketable yield was obtained by subtracting the unmarketable yield from the total tuber yield. The potato HI was expressed as the percentage of total fresh tuber yield (Y) in the total biomass estimated at harvest (Tbh) (total fresh tuber yield plus aboveground biomass at harvest) (equation 4.3). For DM, four tubers randomly chosen from each subplot were washed, chopped and mixed. A sample weighing 200 g was taken and pre-dried at 60 °C for 72 hours (Bekele & Haile, 2019). The dry weight of the sample was taken, and the tuber dry matter content (DM) was computed using the following formula (equation 4.3).

$$DM (\%) = \frac{\text{Dry weight (g)}}{\text{Fresh weight (g)}} \times 100 \dots\dots\dots \text{Equation 4. 3}$$

4.4 Data analysis

Before analysis, data were subjected to the normality test at a probability level of 0.05 (Shapiro–Wilk test) using R software (version 3.6.3) (R-Core-Team, 2020). Analysis of variance (ANOVA) was conducted using equation 3.10. The least-squares means (LSMEANS) test was used to separate the treatment means at the 0.05 significance level. Regression analyses were carried out at the 0.05 significance level to determine total tuber yield, marketable tuber yield and DM responses to N levels in a mollic Andosol. The Pearson correlation coefficient was analysed at a probability level of 0.05 to test the relationship between tuber number per plant and total tuber yield.

4.5 Results and discussion

4.5.1 Difference in soil moisture and cumulative actual crop evapotranspiration

Soil moisture was collected every 2 days before and after every irrigation event until harvest. The results showed that the difference in soil moisture was low during the first four weeks. This can be explained by the fact that the root system of the crop was not well established to facilitate the photosynthetic activities of the crop. A high difference in soil moisture was obtained between 35 and 87 days after planting (DAP) (Fig. 4.1). This consists of the period of tuber initiation to the tuber bulking stages. This indicated that this period formed the critical stage at which a slight water deficit might negatively affect the yield of apical rooted cuttings of potato. Before or after this period, water deficit can also affect potato since the crop requires high soil moisture throughout its growing season. Research conducted

by Yactayo *et al.* (2013) on timely irrigation restriction showed that water restriction initiated in potato between six and eight weeks after planting leads to low potato yield compared to water restriction initiated eight weeks after planting. Djaman *et al.* (2021) reported that the maximum daily potato evapotranspiration of 6.5 mm day^{-1} occurred at the tuber bulking stage. Shock and Feibert (2002) reported that severe water stress at an early stage (vegetative) could reduce potato tuber yield by approximately 40%. Camargo *et al.* (2015) found that soil moisture content should be maintained above 50% of the total available water throughout the growing season for sustainable potato production. A reduction in potato tuber yield by 12% and 42% was found when water stress was imposed at the tuber bulking and maturation stages of potato, respectively (Karam *et al.*, 2014).

Crop evapotranspiration (ETC) is the evapotranspiration from the well-fertilized, disease-free crop cultivated in large fields under optimum soil moisture conditions and achieving full production in a given climatic condition (Allen *et al.*, 1998). The cumulative actual crop evapotranspiration (ET_a) estimated in this study was on average 2001.4, 302.1, 342.4 and 402.8 mm under ETC50%, ETC75%, ETC85% and ETC100%, respectively (Table 4.1). These results agreed with the previous studies that reported that the total seasonal water demand varied from 350 to 800 mm for various climates and environments (Adavi *et al.*, 2018; Afzaal *et al.*, 2020; Ati *et al.*, 2012; Ati *et al.*, 2010; Djaman *et al.*, 2021; Ierna & Mauromicale, 2018; Meligy *et al.*, 2020; Nowacki, 2018; Paredes *et al.*, 2018). Potato water demand for maximum tuber yield depends on climatic conditions and ranges between 500 and 700 mm (Doorenbos & Kassam, 1979). In Peru, it was reported that potato ET_a varied from 400 to 800 mm (Haverkort, 1982). Another study estimated the potato water demand for optimum yield in California at 316 to 630 mm (Djaman *et al.*, 2021). Karam *et al.* (2014) reported seasonal irrigation water demand for potato in a semi-arid region of Lebanon at 500–560 mm. The average water demand for a high potato yield in Saudi Arabia was estimated at 1505 mm (El-Abedin *et al.*, 2017). Potato water demand also depends on soil type and irrigation management practice (Chen *et al.*, 2019a). Cumulative potato crop evapotranspiration was estimated respectively at 413.2 and 362.1 mm in loam and clay soil (Katerji *et al.*, 2011).

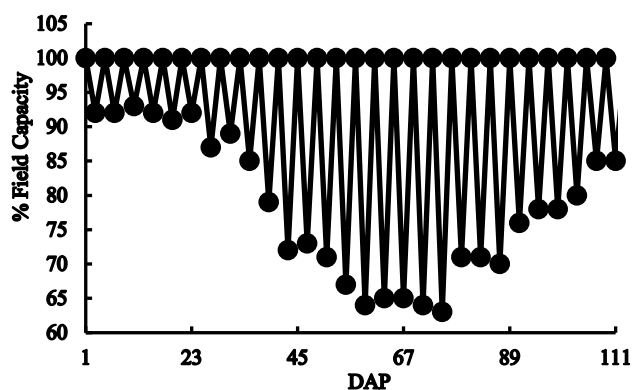


Figure 4. 1: Difference in soil moisture under ETC100%.

Table 4.1: Cumulative actual crop evapotranspiration (mm) of the growing seasons

	ETC100%	ETC85%	ETC75%	ETC50%
Season one	398.3	338.5	298.7	199.1
Season two	407.3	346.2	305.5	203.7

4.5.2 Effects of N and irrigation regimes on the growth of potato

The effect of N rates and irrigation regimes on potato growth are presented in Tables 4.2 and 4.3. The averages of potato height and number of branches per plant were statistically ($P < 0.001$) affected by N. However, irrigation and irrigation \times nitrogen did not exhibit a significant ($P > 0.05$) effect on these growth parameters. A similar observation was made by Darabad (2014), who found that an irrigation amount did not interfere with plant height. However, many studies reported that potato crop height increased with an increment in irrigation amount applied (Farrag *et al.*, 2016; Metwaly & El-Shatoury, 2017; Zhang *et al.*, 2017b). This difference in result can be attributed to the plant material utilized, the soil type or the environment.

The height and number of branches per plant widely varied under different N rates. The highest plant height (92.67 cm) was obtained with 130 kg N ha⁻¹, whereas the lowest (80.79 cm) was observed under control (0 kg N ha⁻¹), but it is not statistically different from the plant height obtained with 60 kg N ha⁻¹. The number of branches per plant also increased significantly with the amount of N applied. The highest number of branches per plant (17) was obtained with an application of 130 kg N ha⁻¹, whereas the smallest (11) was obtained with 0 kg N ha⁻¹. Similar observations were obtained in previous studies (Godebo & Belay, 2020; Setu & Mitiku, 2020; Tolessa *et al.*, 2017). Sebnie *et al.* (2021) reported that an application of mineral N fertilizer increased potato plant height compared to unfertilized plots.

Table 4.2: Means squares of plant height, number of branches, number of tubers per plant, total yield, marketable yield, harvest index (HI) and tuber dry matter content (DM) under different N and irrigation regimes

Source of variation	df	Plant height	Number of branches	Number of tubers per plant	Total yield	Marketable yield	HI	DM
Season	1	640.67	5.51	0.51	73.45	75.26	8.37	28.83*
Replicate(season)	4	418.82	1.29	5.79	1.13	1.80	94.53	10.66
Irrigation	3	118.69	27.12	67.68	964.98***	964.93***	423.99***	30.74
Season×irrigation	3	196.64	2.54	10.34	27.88	18.74*	41.81	5.99
Replicate×irrigation(season) (Ea)	12	99.57	1.78	8.63	16.32	13.25	27.03	3.68
Nitrogen	3	591.03***	127.59***	164.98***	2565.75***	2709.25***	57.81**	89.32***
Season×nitrogen	3	8.14	0.18	3.04	1.52	2.13	8.43	11.91
Irrigation×nitrogen	9	120.50	1.07	10.93	58.91***	68.17**	94.32***	18.42
Season×irrigation×nitrogen	9	89.04	0.87	9.58	15.55	8.03	14.60	19.53
Error (Eb)	48	61.02	2.16	5.10	6.65	6.72	12.03	11.20
R ²		0.74	0.83	0.81	0.97	0.97	0.85	0.62
CVa		11.48	9.00	14.73	11.31	11.74	10.77	7.02
CVb		8.99	9.92	11.33	7.22	8.35	7.19	12.25

Ea = error of the main plots, Ea = error of the subplots, CVa = coefficient of variation for the main plots, CVb = coefficient of variation for the subplots. ‘***’, ‘**’ and ‘*’ are significance codes at 0.001, 0.01 and 0.05, respectively.

Table 4.3: Means of plant height, number of branches per plant under different N treatments

N-treatment	Plant height	Number of branches per plant
N3	92.67a	17a
N2	88.38ab	15b
N1	85.83bc	14c
N0	80.79c	11d
LSD	4.7714	0.7827

Same letters in the same column indicate no significant difference, while different letters indicate a significant difference at a significant level of 0.05.

4.5.3 Effects of N and irrigation regimes on potato yield and its components

Irrigation×nitrogen effect on total fresh tuber yield and marketable tuber yield of potato was significant ($P < 0.001$). However, the tuber number per plant was only affected by N ($P < 0.001$) (Table 4.2). Application of 130 kg N ha⁻¹ resulted in the highest total tuber yield under different irrigation regimes (Table 4.4). A significant reduction in total tuber yield was also found when applying less irrigation. The lowest total tuber yield responses were observed in ETC50%, whereas the highest responses were found in ETC100%. This showed the sensitivity of apical rooted cuttings of potato to water deficit during its cycle. Reduction in fresh tuber yield because of the progressive water stress averaged 8.62% with 15% (ETC85%) in reduction of irrigation amount. Besides, a reduction in the amount of irrigation applied by 25% (ETC75%) and 50% (ETC50%) reduced the total tuber yield by 15.90% and 35.57%, respectively, under average different N-fertilization. For the interaction, the highest total tuber yield was observed under ETC100% with 130 kg N ha⁻¹, while the lowest was found under deficit treatment when the irrigation treatment was reduced by 50% (ETC50%) with 0 kg N ha⁻¹ (Table 4.4).

Full irrigation (ETC100%) usually produces the highest potato tuber yield (Badr *et al.*, 2012; Bani-Hani *et al.*, 2018; Shock & Feibert, 2002). Previous research indicated that total fresh tuber yield generally increased with an increment in the amount of irrigation applied (Camargo *et al.*, 2015; Yuan *et al.*, 2003). A significant potato tuber yield reduction was observed when growing potato under ETC70% in silty-clay soil compared to full irrigation (Fleisher *et al.*, 2008). Bohman *et al.* (2019) reported a potato yield of 72.5 t ha⁻¹ under ETC100% with an application of 270 kg N ha⁻¹ in frigid entic Hapludolls soil in Becker, while

Maltas *et al.* (2018) reported a total tuber yield of 73.7 t ha⁻¹ with 200 kg N ha⁻¹ in calcareous Cambisol in Agroscope-Changins. This showed that the N requirement for a high potato yield depends on the soil type.

The marketable yield is the most interesting part for farmers. This study showed that the marketable tuber yield under different irrigation regimes and N rates varied between 11.19 and 54.25 t ha⁻¹. The marketable tuber yield under different N rates decreased with the increment of the water stress. The reduction in irrigation amount in a mollic Andosol by 15% (ETC85%), 25% (ETC 75%) and 50% (ETC50) resulted in a decrease in marketable tuber yield by 10.01, 15.53 and 40.31%, respectively, under different N-fertilization (Table 4.4). This showed that an increment of N in water stress conditions in a mollic Andosol could not significantly change the marketable tuber yield of apical rooted cuttings of potato, probably due to an adverse effect of excessive mineral N application on potato yield. Begum *et al.* (2018) indicated that suppression of water deficit in potato production could lead to high and stable yields of potatoes at 40–50 t ha⁻¹ or more. The unexpected response of total fresh tuber yield and marketable tuber yield of potato to N level obtained in all irrigation treatments was also reported (Badr *et al.*, 2012; Ospina *et al.*, 2014; Shunka *et al.*, 2017).

The significance of the interaction effect of the two factors for total tuber yield and marketable tuber yield showed that both factors were important for the increase observed in total tuber yield and marketable potato tuber yield in a mollic Andosol. Badr *et al.* (2012) and Elmetwalli and Elnemr (2020) indicated that irrigation×nitrogen significantly affected potato yield. However, Bohman *et al.* (2019) reported that irrigation×nitrogen had no significant effect on potato yield and marketable tuber yield. Tolessa (2019) indicated that an application of 207 kg N in rain-fed potato production could increase potato yield and marketable tuber yield by approximately 176% and 119%, respectively, compared to the unfertilized plot. Sebnie *et al.* (2021) reported that marketable potato yield generally increases with the N rate and a high marketable yield of 45.5 t ha⁻¹ can be achieved when applying 138 kg N ha⁻¹. However, a fieldwork study in Ethiopia recorded a marketable potato yield of 25.5 t ha⁻¹ when 150 kg N ha⁻¹ was applied. The high marketable potato yield of 54.25 t ha⁻¹ obtained in a mollic Andosol in this study can be related to the significant interaction between the two factors. These results are in agreement with those of Zewide *et al.* (2012), Getie *et al.* (2015), El Mokh *et al.* (2015), Regassa *et al.* (2016), Ayyub *et al.* (2019), Setu and Mitiku (2020) and (Tang *et al.*, 2021). They found that marketable potato yield generally increases with N dosage. This study suggests further research using higher N rates above the rates used to find the N level from which an

increase in the amount of N in a mollic Andosol might result in a decrease in total tuber yield and marketable tuber yield.

The highest tuber number per plant (23) was found when 130 kg N ha⁻¹ was applied (Fig. 4.3). The Pearson correlation showed that the total tuber yield was significantly correlated with the tuber number per plant ($r = 0.7^{***}$) (Fig. 4.2). The further correlation analyses showed that the total tuber yield significantly depended on the number of ware potato ($r = 0.59^{***}$) and size two (C2) ($r = 0.53^{***}$) tubers per plant (Table 4.5). This result implied that for obtaining an optimum potato yield in a mollic Andosol, the water and N management that leads to a high number of C2 and ware should be practiced by potato farmers. This study did not confirm the findings of Fandika *et al.* (2016) and El Mokh *et al.* (2015), who found that tuber number per plant increased with irrigation amount. This finding is in line with the results of Ayyub *et al.* (2019) and Setu and Mitiku (2020), who also reported an increase in tuber number per plant with an increment in N dosage. El Mokh *et al.* (2015) also indicated that the decrease in tuber number per plant decreased the total tuber yield. On the contrary, Badr *et al.* (2012) reported no significant correlation between tuber number per plant and total tuber yield.

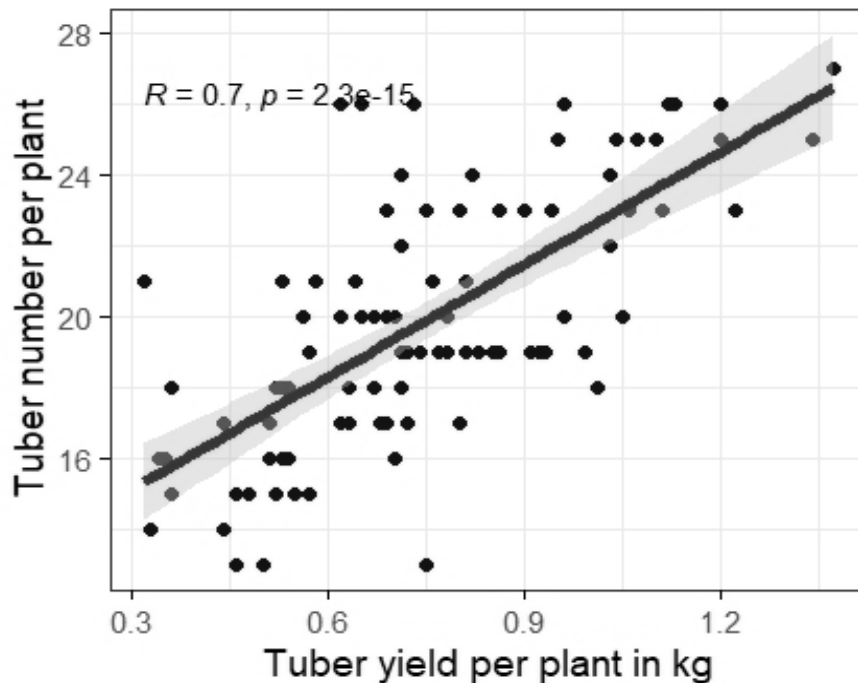


Figure 4.2: Correlation between tuber number per plant and tuber yield

Table 4.4: Interaction means of total tuber yield, marketable tuber yield, and HI

Irrigation regime	N rate (kg N ha ⁻¹)	Total tuber yield (t ha ⁻¹)	Marketable yield (t ha ⁻¹)	HI (%)
ETC100%	N0	28.41hi	23.49g	40.85h
	N1	33.66fg	28.66ef	47.60defg
	N2	47.78c	41.97c	47.47def
	N3	58.29a	54.21a	43.15gh
ETC50%	N0	16.38k	11.21i	45.52eg
	N1	26.30i	20.54gh	56.49a
	N2	30.90gh	27.35f	54.68ab
	N3	34.99ef	29.62ef	57.12a
ETC75%	N0	22.15j	17.51j	47.91def
	N1	34.06f	30.43f	50.99bcd
	N2	38.36de	34.08de	48.96cde
	N3	46.78c	43.45c	51.86bc
ETC85%	N0	26.80i	21.32i	49.66cde
	N1	35.68ef	31.21ef	40.94h
	N2	39.67d	34.16d	43.64fgh
	N3	51.33b	46.87b	45.49efg

Same letters in the same column indicate no significant difference, while different letters indicate a significant difference at a significant level of 0.05.

Table 4.5: Correlation between different potato sizes and tuber yield per plant

Tuber yield per plant	-0.19	0.21*	0.53***	0.59***
	Chat	0.012	-0.08	-0.22*
		Size one (C1)	0.30*	0.17
			Size two (C2)	0.38*
				Ware tuber

Significance codes at P < 0.001 '***', P < 0.01 '**', P < 0.05 '*'.

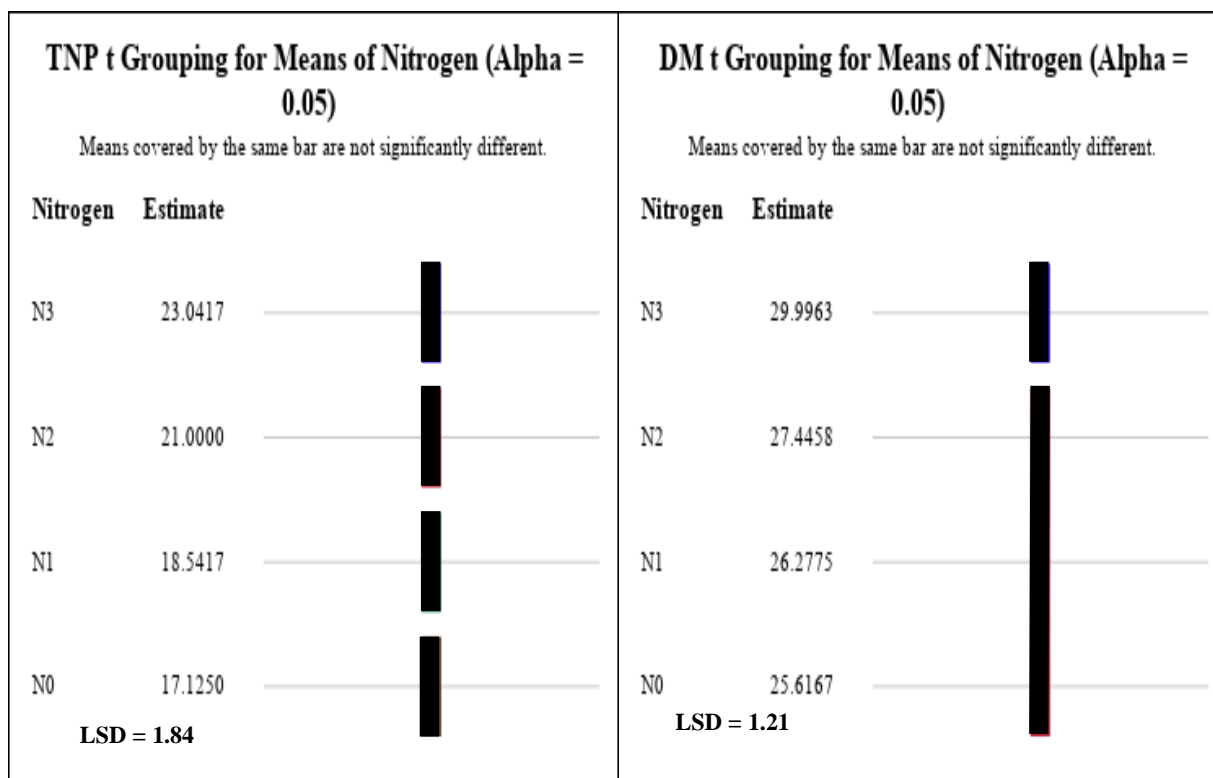


Figure 4.3: Means separation of tuber number per plant and tuber dry matter content across N rates. TNP = tuber number per plant and DM = tuber dry matter.

N-fertilization only exhibited a significant ($P < 0.01$) effect on potato tuber dry matter content (Table 4.2). A comparison of DM across N rates indicated the highest DM under 130 kg N ha⁻¹ while the smallest DM under 0 kg N ha⁻¹ (Fig. 4.3). The tuber dry matter in different irrigation regimes did not differ significantly, but the highest, 28.53%, and lowest, 25.81%, values of DM regardless of N rate were found under ETC75% and ETC100%, respectively. Kashyap and Panda (2003) and Karam *et al.* (2014) reported a high DM under water stress treatment than DM collected under ETC100%. However, Darwish *et al.* (2006) reported that DM increases with an increment of irrigation from ETC60% to ETC100% and then tends to decline as irrigation amount increases. Fleisher *et al.* (2008) and Camargo *et al.* (2015) indicated that severe water stress generally affected DM. Milroy *et al.* (2019), Ayyub *et al.* (2019) and Maltas *et al.* (2018) showed that DM increased with N rates. The results of this study differed with contradicted the findings of Sharifi *et al.* (2005) and Janat (2007), who found no significant increase in DM with an increase in N rate. Further, the results of this study did not tally with the findings of Ahmed *et al.* (2009) that DM declined with N application.

4.5.5 Production functions

The production functions of total tuber yield, marketable tuber yield and DM were developed for different irrigation regimes to show their responses to N levels in different water stress conditions in a mollic Andosol (Fig. 4.4 a, b and 4.5) (all F-values in the analysis were significant at $P < 0.05$). The relationship between total tuber yield and marketable tuber yield and applied N showed a linear relationship. Linear regression was also observed between DM and N rates. The regression equations and determination coefficients between N-fertilization and total tuber yield obtained in the different irrigation regimes were:

$$\text{ETC100\%: } Y = 0.24X + 25.43, R^2 = 0.91 \dots\dots\dots \text{Equation 4. 4}$$

$$\text{ETC85\%: } Y = 0.18X + 25.61, R^2 = 0.96 \dots\dots\dots \text{Equation 4. 5}$$

$$\text{ETC75\%: } Y = 0.19X + 22.18, R^2 = 0.99 \dots\dots\dots \text{Equation 4. 6}$$

$$\text{ETC50\%: } Y = 0.14X + 16.39, R^2 = 0.99. \dots\dots\dots \text{Equation 4. 7}$$

These equations indicated that total potato tuber yield increased respectively by about 240, 180, 190 and 140 kg ha^{-1} for each kg of N applied in a mollic Andosol under ETC100%, ETC85%, ETC75% and ETC50%. This showed that from 0 to 130 kg N ha^{-1} an increase in a unit of N greatly increased total potato tuber yield under ETC100% compared to deficit treatments. However, the slope obtained under ETC85% did not differ from the one observed in ETC75%. This indicated that the increment of total potato tuber yield for each kg of N applied under ETC85% in a mollic Andosol did not differ significantly from the increase in total tuber yield after each kg of N applied under ETC75%.

The linear regression equations and determinations coefficients between N-fertilization and marketable tuber yield were:

$$\text{ETC100\%: } Y = 0.24X + 20.27, R^2 = 0.90 \dots\dots\dots \text{Equation 4. 8}$$

$$\text{ETC85\%: } Y = 0.17X + 19.28, R^2 = 0.95 \dots\dots\dots \text{Equation 4. 9}$$

$$\text{ETC75\%: } Y = 0.15X + 17.66, R^2 = 0.99 \dots\dots\dots \text{Equation 4. 10}$$

$$\text{ETC50\%: } Y = 0.13X + 11.80, R^2 = 0.96 \dots\dots\dots \text{Equation 4. 11}$$

The slopes obtained indicated that for each kg of N applied, the marketable tuber yield increased by about 240, 170, 150 and 130 kg ha^{-1} under ETC100%, ETC85%, ETC75% and ETC50%, respectively. All the production functions had a high coefficient of determination above 0.90. These functions also showed that marketable tuber yield obtained in ETC100% responded very well to N dosage compared to other irrigation treatments. Since irrigation regimes did not interfere with DM, the combined data from different plots were used to analyze

the relationship between DM and N rate. The following regression equation and determination coefficient were obtained:

$$Y = 0.03X + 24.95, R^2 = 0.84 \dots\dots\dots \text{Equation 4. 12}$$

It was observed that an increment of each kg of N applied increased the DM of potato by approximately 0.03%.

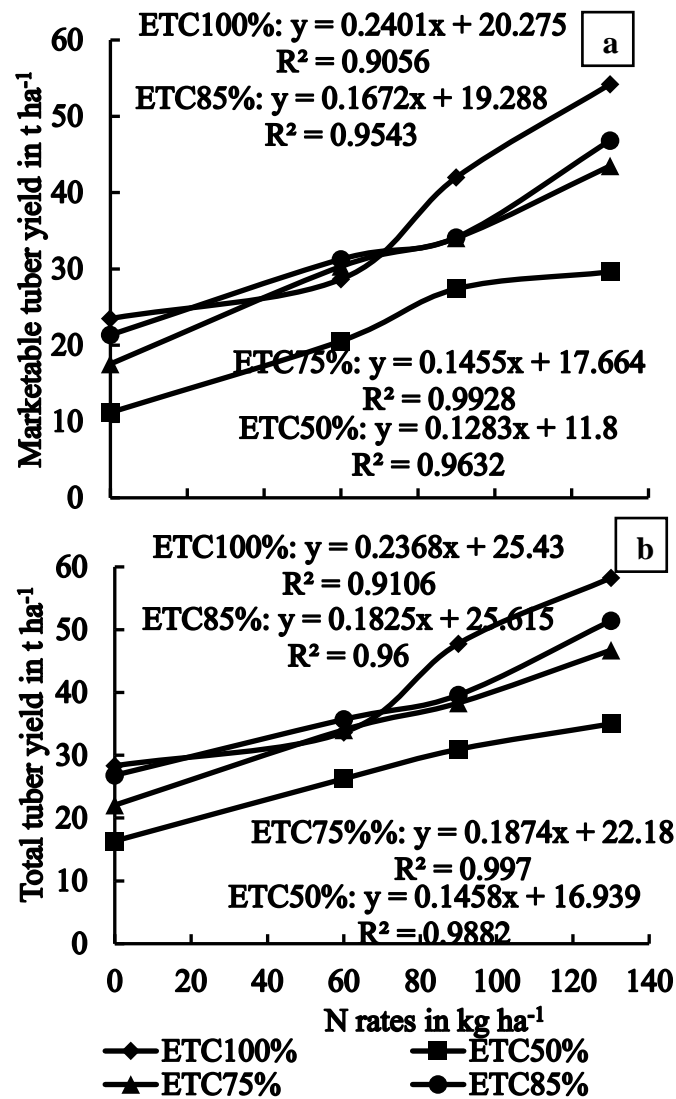


Figure 4.4: Relationship between N rate and both total tuber yield and marketable tuber yield under different irrigation regimes.

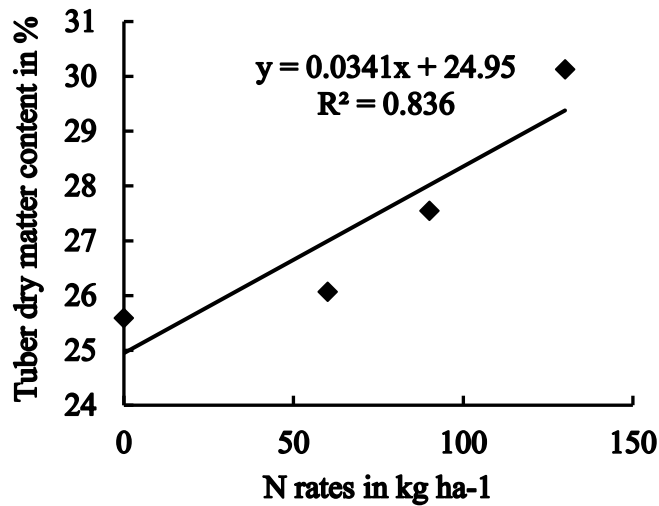


Figure 4.5: Relationship between DM and N rate.

4.6 Conclusion

Irrigation and N-fertilization are the key factors in potato production. This study shows that the tuber initiation and tuber bulking stages represent the critical water demand for potato. The cumulative actual crop evapotranspiration (ET_a) estimated in this study was on average 201.4, 302.1, 342.4 and 402.8 mm under ETC50%, ETC75%, ETC85% and ETC100%, respectively. Plant height, number of branches per plant, tuber number per plant and tuber dry matter are generally responsive to N rate. In contrast, total tuber, marketable yield and harvest index are generally more responsive to both factors than a single factor. This study recommends an irrigation regime of ETC100% and N fertilizer rate of 130 kg N ha⁻¹ in three split applications at 10 (40%), 30 (40%) and 50 (20%) days after planting for a maximum potato yield in a mollic Andosol in Kenya.

CHAPTER FIVE
EFFECTS OF NITROGEN AND IRRIGATION REGIMES ON WATER AND
NITROGEN USE EFFICIENCIES OF POTATO GROWN IN A MOLLIC
ANDOSOL

Abstract

Water and nitrogen (N) are key interacting factors that control plant growth. The objective of the study was to determine the effect of N rates and irrigation regimes on water use efficiency and nitrogen use efficiency of potato grown in a mollic Andosol. A randomized complete block design (RCBD) in a split-plot arrangement was used. The main plot treatments comprised four irrigation regimes: ETC100%, ETC85%, ETC75% and ETC50%, where ETC100% was irrigated according to the soil water depletion 2 days after full irrigation. The sub plot treatments were four N rates: 0 (N0), 60 (N1), 90 (N2) and 130 kg N ha⁻¹ (N3). The results showed that potato tuber yield, water use efficiency (WUE) and nitrogen use efficiency (NUE) were significantly ($P < 0.001$) affected by irrigation regimes, N rates ($P < 0.001$) and the interaction of both factors. The highest potato tuber yield, 58.29 t ha⁻¹, was obtained under ETC100% with N3. The highest WUE, 17.5 kg m⁻³, was found under ETC50% with N3, and the lowest WUE, 7.2 kg m⁻³, was observed under ETC100% with N0, but it was not statistically different from the WUE values obtained under ETC85% and ETC75% with N0. The highest NUE, 208.30 kg kg⁻¹, was recorded in ETC100% with N2, but it did not significantly differ from the NUE values found under the same irrigation treatment with N3. A weak correlation was obtained between WUE and NUE ($r = 0.31^{**}$). A maximum irrigation amount decreased WUE and increased NUE, whereas a high N dosage increased WUE and decreased NUE of potato grown in a mollic Andosol. This study suggests that if farmers aim to maximize WUE of rooted apical cuttings of potato in a mollic Andosol, this would be at the expense of potato NUE and yield would be a secondary target.

Keywords: Irrigation, Nitrogen, Yield, WUE, NUE

5.1 Introduction

After maize, potato (*Solanum tuberosum* L.) is the second most important staple food and cash crop in Kenya. A low yield of potato is obtained in smallholder farms in the country. This is due to a reduction in seasonal rainfall amounts due to climate change and soil nitrogen (N) deficiency occasioned by sub-optimal fertilizer application rates and lack of fallow. Water and N are key interacting factors controlling crop growth (Badr *et al.*, 2012; Fouda *et al.*, 2012). Water enhances root N acquisition by mass flow, whereby water and dissolved nutrients move

from the soil pores into the plant root. This is driven by the physiological process of transpiration (Smethurst, 2004). Water stress reduces the uptake of N as a result of a decrease in water uptake and transpiration rate.

The use of drip irrigation and careful N management in terms of timing, rate and the technique of N application can optimize nitrogen and water use efficiency of potato (Elferink & Schierhorn, 2016) and result in vigorous growth, maximum dry matter accumulation and high marketable yield (Ayyub *et al.*, 2019; Ierna & Mauromicale, 2019; Tolessa, 2019). The use of drip irrigation saves water and minimizes N leaching (Leal Filho *et al.* (2015). Liu *et al.* (2007) reported a saving of 30% of irrigation water when partial root dry irrigation (PRD) was compared to full irrigation. Whereas many studies show that potato responds to water and nitrogen application, this varies depending on soil type, cultivar, crop, climate and environmental conditions (Badr *et al.*, 2012; Djaman *et al.*, 2021; Elmetwalli & Elnemr, 2020; Sebnie *et al.*, 2021; Tang *et al.*, 2021). The objective of the present study was, therefore, to determine the effects of N and drip irrigation watering regimes on water use efficiency and nitrogen use efficiency of *Shangi* potato variety grown in a mollic Andosol in the Kenya highlands.

5.2 Materials and methods

5.2.1 Experimental site description

The experiment was conducted at the research fields of Agro-Science Park, Egerton University in Nakuru County, Kenya. Two separate shelters were set up in the same field for two growing seasons to prevent the residual fertilizer effect (explained in chapter four).

5.2.2 Experimental procedure

The experimental procedure was the same as that of chapter four because WUE and NUE were computed from the data collected in chapter four.

5.3 Data collection

Data recorded on tuber yield and cumulative actual crop evapotranspiration in chapter four were used to compute WUE and NUE. Potato WUE and NUE in a mollic Andosol were computed using equations 3.7 and 3.9 of chapter three, respectively.

5.4 Data analyses

Before analyses, the normality of the data was checked (Shapiro–Wilk test at 0.05) in R software (version 3.6.3). For any not normally distributed data, fitting data transformation was performed. Outlier data were identified using the control chart technique (Bakar *et al.*, 2006). Any outlier data and data not due to the treatment effect were deleted from the model and replaced by the nearest after confirming the data entry error. Analysis of variance (ANOVA) was run using equation 3.10 in chapter 3. The least-squares means (LSMEANS) test was used to separate the treatment means at the 0.05 significance level. The Pearson correlation coefficient was analyzed at a probability level of 0.05 to test the significance of the relationship between WUE and NUE. Regression analyses were carried out at the 0.05 significance level to determine WUE and NUE responses to N dosages and irrigation water regimes in a mollic Andosol.

5.5 Results and discussion

5.5.1 Crop water demand and potato yield

The cumulative actual crop evapotranspiration (ET_a) was on average 2001.4, 302.1, 342.4 and 402.8 mm under ETC50%, ETC75%, ETC85% and ETC100%, respectively. Potato yield was significantly ($P < 0.001$) affected by irrigation regimes, N rates, and both factors' interaction. The tuber yield increased with an increase in irrigation amount and N rate. The highest and the lowest tuber yields were obtained under ETC100% combined with N3 and ETC50% combined with N0, respectively (Table 5.1).

5.5.2 Potato water use efficiency

Water use efficiency varied widely under different irrigation regimes and N rates (Table 5.1). The WUE was significantly affected by irrigation regimes ($P < 0.05$), N rates ($P < 0.001$) and the interaction of both factors ($P < 0.001$). The irrigation amount applied in deficit treatment (ETC50%) regardless of N rate was more efficiently used compared to low deficit treatments. This showed that the WUE generally decreased as the amount of irrigation increased. The highest value, 13.6 kg m⁻³, was recorded at ETC50%. An increment of WUE with the increase in N rate was also observed under all irrigation regimes. The WUE responded well to the N rate rather than the irrigation regime. The results showed that both factors acted together, where the highest, 17.5 kg m⁻³, was found under ETC50% with N3, and the lowest value of WUE, 7.2kg m⁻³, was recorded in ETC100% with N0, but it was not statistically different from the WUE values obtained under ETC85% and ETC75% with N0 (Table 5.2).

The reduction of the irrigation amount by 50% (ETC50%) under N3 increased the WUE by about 20, 17 and 12% compared to ETC100%, ETC85% and ETC75%, respectively. It was also found that WUE responded well to N levels under water stress conditions (ETC50%) in the mollic Andosol compared to other irrigation regimes. The high potato WUE obtained from ETC50% can be related to the least amount of water applied.

These findings did not support the results of Tolessa *et al.* (2016), who reported that WUE obtained from ETC60%, ETC80% and ETC100% were not different. However, findings from this study tallied with earlier studies that reported potato as one of the food crops with a high WUE ranging from 6 to 11.6 kg m⁻³ (Hoekstra, 2008). The high WUE of 17.5 kg m⁻³ can be attributed to the potato genotype used as plant material, the soil type and the irrigation×nitrogen interaction observed in this study. Fandika *et al.* (2016) obtained similar findings and reported that potato WUE is significantly influenced by the genetic material, agronomic practice, irrigation regime, fertilizer dosage, soil type and environmental conditions. This emphasized the importance of determining the WUE of each potato variety on different soil types and in some different environments. Tolessa *et al.* (2016) also observed a significant variety×irrigation interaction effect on WUE of potato in Ethiopia. According to the study conducted by Onder *et al.* (2005), potato WUE ranged from 9.33 to 32.12 5 kg m⁻³, with the highest WUE recorded under ETC33%. El Mokh *et al.* (2015) also reported that potato WUE under drip irrigation varied from 4.9 to 15.6 kg m⁻³. Crop WUE generally declines with the increase in water supply (Badr *et al.*, 2012; Bani-Hani *et al.*, 2018; Djaman *et al.*, 2013; Tolessa, 2019). Elmetwalli and Elnemr (2020) reported that potato WUE was inversely proportional to increasing irrigation amount. Conversely, Darwish *et al.* (2006) and Steyn *et al.* (2007) indicated an increase in potato WUE with an irrigation amount up to ETC100%. N-fertilization is very important for WUE improvement. This study showed that potato WUE response was more due to the N rate than irrigation. El Mokh *et al.* (2015) revealed that an application of N strongly improved potato WUE. This study concluded that potato crops could be grown in a mollic Andosol with an acceptable yield while saving water and minimizing N amount.

Table 5.1: WUE and NUE mean squares under different N and irrigation regimes under different N and irrigation regimes

Source of variation	df	WUE	Source of variation	df	NUE
Season	1	3.55	Season	1	599.39
Replicate(season)	4	0.11	Replicate(season)	4	53.75
Irrigation	3	40.70***	Irrigation	3	6127.33***
Season×irrigation	3	2.80	Season×irrigation	3	87.18
Replicate×irrigation(season) (Ea)	12	1.54	Replicate×irrigation(season)) (Ea)	12	213.80
Nitrogen	3	278.47***	Nitrogen	2	23697.19***
Season×nitrogen	3	0.06	Season×nitrogen	2	324.55
Irrigation×nitrogen	9	3.90***	Irrigation×nitrogen	6	1586.02***
Season×irrigation×nitrogen	9	1.46*	Season×irrigation×nitrogen	6	173.94
Error (Eb)	48	0.56	Error (Eb)	32	108.78
R ²		0.97	R ²		0.96
CVa		10.51	CVa		8.95
CVb		6.34	CVb		6.38

Ea = error of the main plots, Ea = error of the subplots, CVa = coefficient of variation for the main plots, CVb = coefficient of variation for the subplots. ‘***’, ‘**’ and ‘*’ are significance codes at 0.001, 0.01 and 0.05, respectively.

Table 5.2: Treatment means separation of tuber yield and WUE under different N and irrigation regimes

Irrigation regime	N rate N (kg ha ⁻¹)	Tuber yield (kg ha ⁻¹)	WUE (kg m ⁻³)
ETC100%	N0	28.41hi	7.117h
	N1	33.66fg	8.432g
	N2	47.78c	11.965de
	N3	58.29a	14.597b
ETC50%	N0	16.38k	8.205g
	N1	26.30i	13.175c
	N2	30.90gh	15.4783b
	N3	34.99ef	17.523
ETC75%	N0	22.15j	7.393gh
	N1	34.06f	11.370ef
	N2	38.36de	12.810cd
	N3	46.78c	15.620b
ETC85%	N0	26.80i	7.895gh
	N1	35.68ef	10.510f
	N2	39.67d	11.688e
	N3	51.33b	15.127b

Same letters in the same column indicate no significant difference, while different letters indicate a significant difference at a significant level of 0.05. WUE = water use efficiency.

5.5.3 Potato nitrogen use efficiency

There were significant differences in nitrogen use efficiency (NUE) between various irrigation regimes and N rates (Tables 5.1 and 5.2). Both factors and their interaction statistically ($P < 0.001$) affected the NUE (Table 20). Nitrogen use efficiency in various irrigation regimes and N rates ranged from 109.77 to 208.30 kg kg⁻¹ N. Low NUE was observed in ETC50% under all N-fertilizations (Table 18). The reduction in irrigation amount was accompanied by NUE reduction under all N-fertilizations. This can be attributed to the low availability of N in water stress conditions since the highest NUE was obtained under ETC100%. This showed that both factors did not react separately in a mollic Andosol. The NUE generally increased with the N rate up to 90 kg N ha⁻¹. However, NUE tended to decrease by about 0.2% when N supplied was above 90 kg N ha⁻¹ under ETC100% and ETC50%. This showed that an increase in the amount of N above 90 kg N ha⁻¹ in full irrigation treatment

(ETC100%) or water deficit conditions (ETC50%) could decrease NUE. The highest NUE, 208.30 kg kg⁻¹ N, was obtained in ETC100% with N2, but it did not significantly differ from the NUE values observed under the same irrigation treatment with N3.

The findings agreed with Fandika *et al.* (2016) and Liu *et al.* (2012), who found that NUE increased with the increase in irrigation amount. Fandika *et al.* (2010) reported that NUE increment depended on the potato genotype. Increasing irrigation amount from ETC60% to ETC100% could increase potato NUE by 26.2 to 104.2%, depending on the genotype and the soil type. On the contrary, Djidonou *et al.* (2013) reported an increase in potato NUE with the reduction in irrigation amount. The nitrogen status of the growing soil also affects NUE. The same trend was reported by Badr *et al.* (2012) and Tolessa *et al.* (2017). Ierna and Mauromicale (2019) reported the highest potato NUE when applying 100 kg N ha⁻¹. Ospina *et al.* (2014) indicated that potato NUE generally decreases with an increase in N dosage. However, some potato varieties presented an increase in NUE with an N rate up to 180 kg N ha⁻¹. Maltas *et al.* (2018) recorded the highest potato NUE at 120 kg N ha⁻¹. Badr *et al.* (2012) and Zotarelli *et al.* (2008) explained this decrease in potato NUE with N dosage by the ability of potato to extract more N from the soil when it is grown in a nitrogen-limited soil. However, Tolessa *et al.* (2017) indicated that the N rate did not affect potato NUE. Potato NUE is also influenced by soil type, soil depth and drainage, and other nutrient statuses in the growing soil (Maresma *et al.*, 2016). This study showed improved NUE in mollic Andosol under full irrigation (ETC100%) combined with 90 kg N ha⁻¹.

The Pearson correlation showed that the WUE was significantly correlated with NUE ($r = 0.31^{***}$) (Fig. 5.1). The correlation was, however, weak. This indicated that other factors were involved. This suggests a need to explore these factors further to find the best NUE and WUE that would result in optimum yield and high-quality tubers. Irrigation and N rate influenced NUE and WUE. Maximum irrigation amount reduced WUE and increased NUE, whereas high N dosage increased WUE and decreased NUE of potato grown in a mollic Andosol. Therefore, if maximizing WUE in a mollic Andosol is the purpose of the farmers, then it should be at the expense of potato NUE and yield should be considered as a secondary target. These findings have a strong implication for potato grown under water stress in a mollic Andosol.

Table 5.3: Treatment means separation for NUE under different N and irrigation regimes

Irrigation regime	N rate (kg N ha ⁻¹)	NUE (kg kg ⁻¹ N)
ETC100%	N1	119.132e
	N2	208.303a
	N3	207.792a
ETC50%	N1	109.778e
	N2	150.093c
	N3	149.758c
ETC75%	N1	146.572cd
	N2	177.700b
	N3	181.493b
ETC85%	N1	134.593d
	N2	172.492b
	N3	203.85a

Same letters in the same column indicate no significant difference, while different letters indicate a significant difference at a significant level of 0.05. NUE = nitrogen use efficiency.

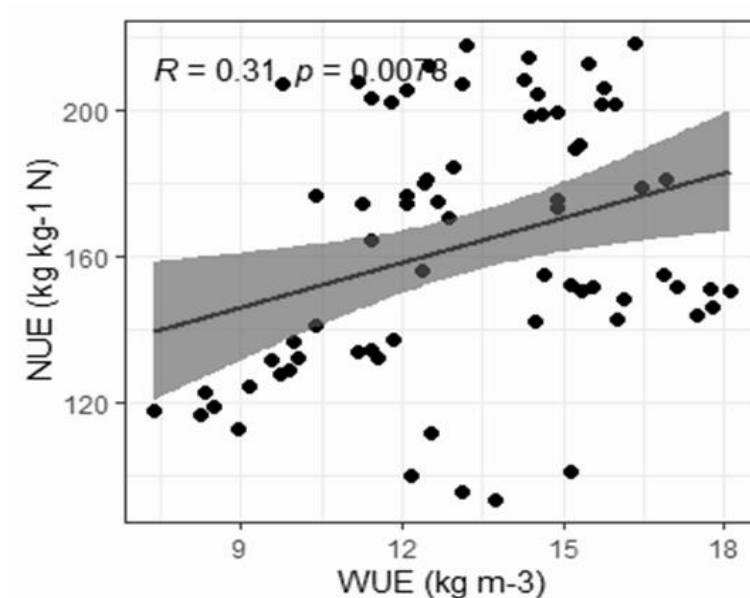


Figure 5.1: Correlation between NUE and WUE of potato.

5.5.4 Production function

The production functions show the responses of WUE and NUE to N rate in different water deficit conditions in a mollic Andosol (Fig. 5.2 a and b). The relationships between WUE and NUE and N applied were linear, with high coefficients of determination above 0.90 ($P < 0.05$). From 0 to 130 kg N ha⁻¹, the increase in WUE for each kg of N applied increased as the

water deficit became severe. Moreover, for each kg of N applied, WUE increased by about 0.051, 0.054, 0.063 and 0.073 kg m⁻³ under ETC100%, ETC85%, ETC75% and ETC50%, respectively. This showed the best WUE response to N levels under ETC50%. On the contrary, NUE significantly increased for each unit of N applied up to 90 kg ha⁻¹. Above 90 kg N ha⁻¹, the trend tended to decrease after each kg of N applied in ETC100%, ETC75% and ETC50%. The unexpected response of NUE to N under ETC85% requires further research. This implies that for high NUE in a mollic Andosol, farmers should apply about 90 kg N ha⁻¹ since the addition of N above 90 kg N ha⁻¹ could not increase NUE of potato grown in a mollic Andosol.

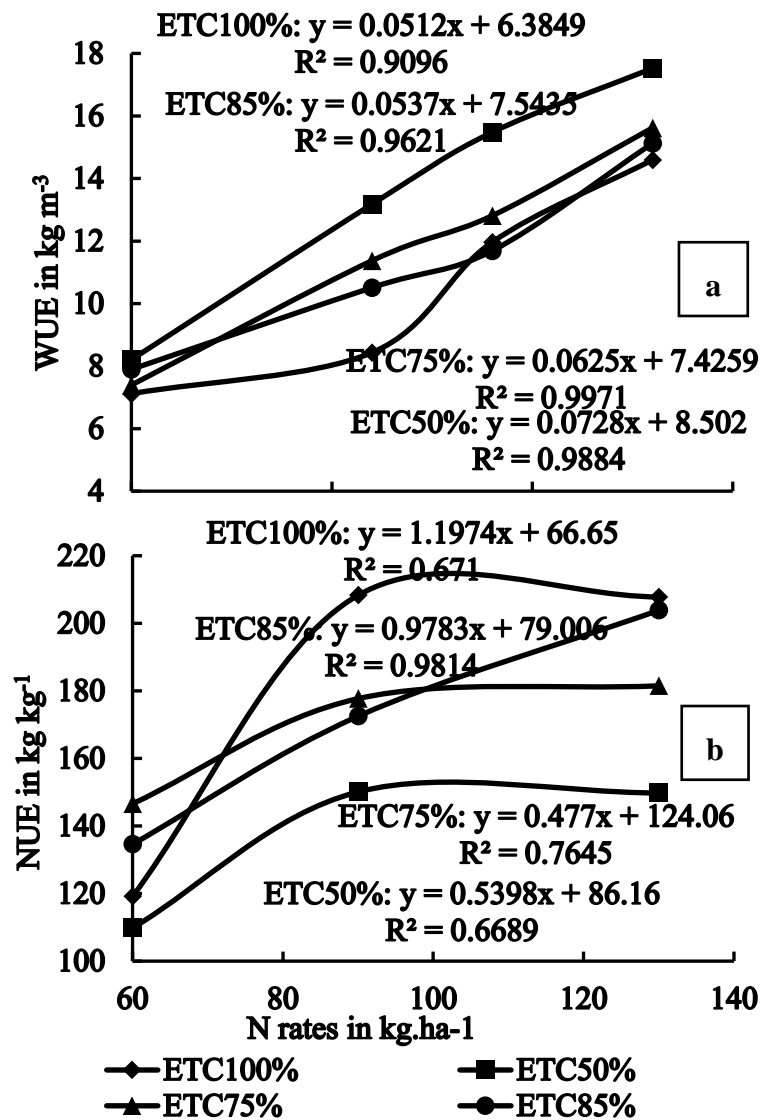


Figure 5.2: Relationship between N rate and both WUE and NUE

5.6 Conclusion

Careful N management in terms of time, rate, and N application method is essential to achieve high potato yield while saving water and reducing N losses and considering the high cost of irrigation water and fertilizer. This study shows that potato tuber yield increases with an irrigation amount and N rate increment. Maximum irrigation reduces WUE and increases NUE, whereas high N dosage increases WUE and decreases the NUE of potato. Therefore, if maximizing WUE in a mollic Andosol is the purpose of the farmers, then it should be at the expense of potato NUE and yield should be considered as the secondary target. For high NUE in a mollic Andosol, this study suggests that farmers apply about 90 kg N ha⁻¹.

CHAPTER SIX
POSSIBILITY OF THE USE OF LEAF CHLOROPHYLL CONTENT AND
NORMALIZED DIFFERENCE VEGETATION INDEX FOR IN-SEASON N
ASSESSMENT AND POTATO YIELD PREDICTION

Abstract

Mineral N has high economic and environmental impacts on potato production. The objective of this study was to determine the effects of N rates and irrigation regimes on leaf chlorophyll content, normalized difference vegetation index (NDVI) values and leaf N content collected at different growth stages of potato. A randomized complete block design (RCBD) in a split-plot arrangement was used. The treatments in the main plots comprised four irrigation regimes of ETC100%, ETC85%, ETC75% and ETC50%, where ETC100% was irrigated according to the soil water depletion 2 days after full irrigation. The subplot treatments were four N rates of 0 (N0), 60 (N1), 90 (N2) and 130 kg N ha⁻¹ (N3). The results showed the lowest leaf chlorophyll, NDVI and % N leaf at different potato stages under ETC100%, ETC50% and ETC50%, respectively. The leaf chlorophyll, NDVI and % N significantly increased with the N rate. It was observed that crop stage, irrigation×nitrogen, irrigation×stage and nitrogen×stage had a significant effect on leaf chlorophyll, NDVI and % N leaf. The highest correlation coefficient between % N leaf and leaf chlorophyll ($r = 0.59^{***}$) was obtained at DAP88 while the highest correlation coefficient between % N leaf and NDVI ($r = 0.57^{***}$) was obtained at DAP67. The highest correlation coefficient between fresh potato tuber yield and % N leaf, $r = 0.81^{***}$, and between fresh potato tuber yield and leaf chlorophyll, $r = 0.56^{***}$, were obtained at DAP67. However, the highest correlation coefficient between fresh potato tuber yield and NDVI, $r = 0.62^{***}$, was found at DAP57. This study recommends the use of leaf chlorophyll and NDVI values for in-season N and yield prediction at 57 DAP and 67 DAP that correspond to vegetative to tuber initiation stages of potato. However, leaf chlorophyll and NDVI values might show a strong correlation with the available soil moisture.

Keywords: % N leaf content, Irrigation, Leaf chlorophyll, NDVI, Stages

6.1 Introduction

Achieving high crop yield and quality while minimizing input costs and negative environmental impacts is the main goal of precision agriculture. The potential growth and productivity of various crops depend on weather conditions, topography, soil types and their properties, irrigation and fertilizer application (Bouraoui & Grizzetti, 2014; Chlingaryan *et al.*, 2018; Peng *et al.*, 2021; Zamanian *et al.*, 2018; Zhang *et al.*, 2015). Nitrogen (N) is an important

element for the high productivity of various crops. It is one of the major nutrients for potato growth because it plays an important role in photosynthetic activities, chlorophyll accumulation, potato tuber yield, and tuber dry matter accumulation (Chlingaryan *et al.*, 2018). The values of other nutrients might not be fully achieved if N is not applied at its optimum level (Marouani *et al.*, 2015). At the same time, mineral N has high economic and environmental impacts. It is well known that excessive N-fertilization to potato leads to high potato vine growth at the expense of tuber yield, low tuber quality, low nitrogen-fertilizer use efficiency as well as N losses that might cause environmental pollution by nitrous oxide and groundwater pollution by nitrate (Goffart *et al.*, 2008). On the other hand, Low N application leads to low potato yield (Dunn *et al.*, 2018). This is due to its shallow root system compared to other crops like sugar beet (*Beta vulgaris*), maize (*Zea mays*), or wheat (*Triticum aestivum*) (Zarzyńska *et al.*, 2017).

The optimization of N use efficiency has become an objective of several spectrometric studies (Ayyub *et al.*, 2019; Cao *et al.*, 2015; Chen *et al.*, 2008; Goron *et al.*, 2017; Ierna & Mauromicale, 2019; Lee *et al.*, 2019; Li *et al.*, 2019; Lukina *et al.*, 2001; MacKerron *et al.*, 1993; Maresma *et al.*, 2016; Quemada *et al.*, 2014; Raun *et al.*, 2005; Tang *et al.*, 2021; Wang *et al.*, 2019; Zaeen, 2020). Hence, a split N application method in potato production is seen as the best way to increase fertilizer use efficiency in potato production. In addition, concerning the total N applied at planting, it has been largely accepted that the establishment of field-specific potato N recommendation at planting cannot be accurate. It is very difficult to accurately estimate the total potato N requirement and soil N supply during the crop cycle (Goffart *et al.*, 2008; Shahnazari *et al.*, 2008; Zaeen, 2020; Zhang *et al.*, 2015; Ziadi *et al.*, 2008). In Kenya, N is one of the major elements in deficit in most of the potato-growing soil due to the continuous production. To achieve high potato productivity, potato farmers of Kenya apply 80% of the total N required by potato at planting based on the universal recommendation. However, it was reported that only 20% of total mineral N supplied at planting is taken up by potato (Bélanger *et al.*, 2000). Therefore, the N management that combines splitting with in-season potato N assessment can generally help match N requirement and supply to improve the N use efficiency of potato (Gianquinto *et al.*, 2004; Sharma *et al.*, 2017b).

Many methods are being investigated to manage N in potato and other main crops like maize and wheat. These are divided into two main methods: non-destructive and destructive methods (Chlingaryan *et al.*, 2018). The common destructive method is a chemical analysis using the Kjeldahl digestion method (Sharma *et al.*, 2017b). The non-destructive method is based on plant N assessment using remote sensing and in-situ data (Cao *et al.*, 2015). Several

sensors have aroused interest for in-season N status assessment and crop yield prediction. These include the GreenSeeker sensor, SPAD chlorophyll meter, Crop Circle ACS-470 sensor, CM-100 chlorophyll concentration meter, Hand Held FieldSpec spectroradiometer sensor (Analytical Spectral Devices, Inc., Boulder, CO, USA), Yara N-Sensor, Crop Circle ACS-430 multiplex sensor and CropScan (Bijay & Ali, 2020; Chlingaryan *et al.*, 2018; Cilia *et al.*, 2014; García-Martínez *et al.*, 2020; Maresma *et al.*, 2016, 2018; Muñoz-Huerta *et al.*, 2013). The GreenSeeker sensor and CM-100 chlorophyll concentration meter are primarily used for N prediction in various crops due to their portable aspects. Despite these tools showing hope for assessing N in various crops (Bijay & Ali, 2020; Zaeen, 2020), few studies reported the effects of water stress on the readings of these tools. The objective of this study was to investigate the possibility of the use of leaf chlorophyll content and normalized difference vegetation index for in-season N assessment and potato yield prediction.

6.2 Materials and methods

6.2.1 Experimental site description

This study was conducted in two different rain shelters in the research field of Agro-Science Park of Egerton University in Nakuru County, Kenya. The four sides of the structure were opened during the daytime to allow air inflow and closed at night. The experimental site was the same as the experiment conducted in Chapter four.

6.2.2 Experimental procedure

The experimental procedure was the same as in Chapter four because data were collected from the same experiment.

6.3 Data collection

Data were collected on fresh tuber yield, % N leaf content, leaf chlorophyll and NDVI values. For yield, data collected on fresh tuber yield in Chapter four were used for this experiment. Composite samples of the leaves were taken from five tagged plants per subplot at 57, 67, 88 and 103 days after planting (DAP) for % N leaf content analysis using the Kjeldahl digestion method (Okalebo *et al.*, 2002). The periods 57, 67, 88 and 103 DAP are identified as the end of the potato crops' vegetative, tuber initiation, bulking and maturation stages, respectively, based on table 11 of FAO (Allen *et al.*, 1998). The chlorophyll content in the leaf was measured on five tagged plants per subplot every two weeks till maturity using a CM-100 chlorophyll concentration meter. Chlorophyll content was assessed on the top leaflet of the

fourth compound leaves from the apexes of plants (Li *et al.*, 2012; Li *et al.*, 2019). The NDVI was also taken every two weeks till maturity using the GreenSeeker sensor. It uses a self-illuminated light source in the near-infrared and red wavelengths (650 ± 10 nm) and (770 ± 15 nm), respectively (Crain *et al.*, 2012).

6.4 Data analyses

Before analysis, data were subjected to the normality test of Shapiro–Wilk at a significance level of 0.05 in R software (version 3.6.3). Analysis of variance (ANOVA) was performed using equation 18 in chapter 3 to test the differences in leaf chlorophyll, NDVI and leaf N at different stages of the crop. To test the effect of the growth stage on leaf chlorophyll, NDVI and leaf N, further ANOVA was performed at a significance level of 0.05 using the following equation (equation 24).

$$Y_{ijklmn} = \mu + S_i + B(i)_j + I_k + SI_{ik} + BI(i)_{jk} + N_l + SN_{il} + IN_{kl} + SIN_{ikl} + G_m + SG_{im} + IG_{km} + SI_{Gikm} + NG_{lm} + SNG_{ilm} + ING_{klm} + SING_{iklm} + \mathcal{E}_{ijklmn}$$

Equation 6. 1

Where; μ = overall mean, S_i = effect of the *i*th season, $B(i)_j$ = effect of the *j*th block within the *i*th season, I_k = effect of the *k*th irrigation, SI_{ik} = interaction effect of the *i*th season and *k*th irrigation, $BI(i)_{jk}$ = error term of the main plots, N_l = effect of *l*th nitrogen rate, SN_{il} = interaction effect of the *i*th season and *l*th nitrogen rate, IN_{kl} = interaction effect of *k*th irrigation and *l*th nitrogen rate, SIN_{ikl} = interaction effect of the *i*th season, *k*th irrigation and *l*th nitrogen rate and \mathcal{E}_{ijklm} = random error term for the subplots, SG_{im} = effect of the *i*th season and *m*th growth stage, IG_{km} = effect of the *k*th irrigation and *m*th growth stage, SIG_{ikm} = interaction effect of the *i*th season, *k*th irrigation and *m*th growth stage, NG_{lm} = effect of *l*th nitrogen rate and *m*th growth stage, SNG_{ilm} = interaction effect of the *i*th season, *l*th nitrogen rate and *m*th growth stage, ING_{klm} = interaction effect of *k*th irrigation, *l*th nitrogen rate and *m*th growth stage, SIN_{ikl} = interaction effect of the *i*th season, *k*th irrigation, *l*th nitrogen rate and *m*th growth stage and \mathcal{E}_{ijklmn} = random error term for the subplots.

Fitting models were evaluated at a significance level of 0.05 to determine the appropriate equation that explained the responses of leaf chlorophyll, NDVI and leaf N to N rate under different irrigation regimes at different growth stages of potato grown in a mollic Andosol. The Pearson correlation coefficient was used for determining the relationship between leaf chlorophyll, NDVI, % N leaf N and fresh tuber yield.

6.5 Results and discussion

6.5.1 Effects of N rates and irrigation regimes on leaf chlorophyll content at different growth stages of potato

Irrigation regime ($P < 0.05$) and nitrogen ($P < 0.001$) interaction effect was significant for leaf chlorophyll content values measured using CM-100 throughout the growing season (Table 6.1). Conversely, the interaction effect of both factors on chlorophyll content was significant ($P < 0.05$) only at DAP57. It was observed that leaf chlorophyll content means of potato across irrigation regimes ranged from 40.366 to 45.778, 34.740 to 39.766, 29.509 to 32.441 and 27.140 to 29.833 at DAP57, DAP67, DAP88 and DAP103, respectively (Table 6.4). The lowest leaf chlorophyll content across irrigation regime treatments regardless of N rate at different stages of potato was observed under ETC100%. The highest values of leaf chlorophyll were found under ETC85% at DAP57, DAP67 and DAP88. At DAP103, the maximum leaf chlorophyll content was found under ETC50%, but it did not differ statistically from the leaf chlorophyll content observed under ETC75% and ETC85%. This implied that leaf chlorophyll content increased with irrigation amount up to ETC85%, then tended to decrease as the amount of irrigation water applied increased at DAP57, DAP67 and DAP88. The same comparison across N rates showed that leaf chlorophyll content varied from 36.651 to 47.779, 31.092 to 41.066, 26.396 to 36.461 and 25.582 to 32.257 at DAP57, DAP67, DAP88 and DAP103, respectively. The highest and lowest values of leaf chlorophyll content across N rates were found with N3 and N0, respectively, throughout the crop cycle. Since the interaction effect of both factors was significant for leaf chlorophyll content at DAP57 of the crop, the means were separated according to the interaction. The maximum leaf chlorophyll content, 50.508, was found under ETC85% with N3. However, the later leaf chlorophyll values did not differ significantly from the one obtained under ETC100% with N3. At that stage, the lowest leaf chlorophyll content, 33.493, was obtained in ETC100% with an application of 0 kg N ha⁻¹. The high significance level of the effect of N on leaf chlorophyll content at all growth stages of the crop showed that leaf chlorophyll content responses were more due to the N rate. It was also found that leaf chlorophyll collected at DAP88 and DAP103 statistically varied across the different seasons. This can be explained by the high temperatures recorded in the rain shelter during the second season, which could have also increased soil temperature.

The leaf chlorophyll is related to the crop greenness, which is always associated with an extensive photosynthetic activity at different crop stages (Thomas & Smart, 1993), leading to a maximum yield in a water-restricted environment in some crops (Tardieu, 2013; Tuberosa, 2012; Vadez *et al.*, 2011). The results of this study agreed with the findings of Ramírez *et al.*

(2014), who reported that potato leaf chlorophyll content increased with irrigation amount. Fouda *et al.* (2012) and Elmetwalli and Elnemr (2020) indicated that potato leaf chlorophyll increased with both applied irrigation amount and N dosage. This study is also in agreement with the results of Saravia *et al.* (2016). They reported that a reduction in both irrigation amount and N rate decreased leaf chlorophyll. However, it did not agree with the findings of Zhang *et al.* (2014), who found that irrigation did not significantly affect leaf chlorophyll. The decrease in chlorophyll under ETC100% can be related to the potato variety used. It is also well known that N is one of the enzymes participating in crop chlorophyll synthesis and is a molecule fraction of chlorophyll. Therefore, an increment in the N rate can enhance the leaf chlorophyll content of the potato (Fabbri *et al.*, 2020; Najm *et al.*, 2012). Although a further increase in N dosage above the optimum level did not improve potato yield, it was reported that an increase in the amount of N applied enhances leaf chlorophyll content values recorded with SPAD-502 (Gianquinto *et al.*, 2004; Ierna & Mauromicale, 2019). This study agreed with the findings of Güler (2009), Zhang *et al.* (2014), Gathungu *et al.* (2016), Saravia *et al.* (2016) and Qiqige *et al.* (2017), who reported that potato leaf chlorophyll content linearly increased with N rate. No consistent assumptions about the effect of irrigation and N on leaf chlorophyll of potato in a mollic Andosol have been made even though this work has been studied by many groups using various crops (Ballester *et al.*, 2017; Bekmirzaev *et al.*, 2019; Gathungu *et al.*, 2016; Li *et al.*, 2019; Mellgren, 2008; Najm *et al.*, 2012; Ning *et al.*, 2021; Peng *et al.*, 2021; Qiqige *et al.*, 2017; Schepers *et al.*, 1992; Swiader & Moore, 2002; Széles *et al.*, 2012; Taskos *et al.*, 2015). This inconsistency in conclusions, especially for potato can be due to the potato genotypes, the form of fertilizers, growth stages, soil types, agronomic practices and the nitrification process (Gao *et al.*, 2014; Qiqige *et al.*, 2017). This study demonstrated that the leaf chlorophyll of potato grown in a mollic Andosol significantly increased with irrigation regime up to ETC85% and then tended to decrease as the irrigation amount increased at different stages of the crop. This study also concluded that leaf chlorophyll content of potato grown in a mollic Andosol significantly increased with N rate and a significant effect of irrigation×nitrogen was observed at DAP57.

Table 6.1: Mean squares of leaf chlorophyll content collected with CM-100 at different stages of potato

Source of variation	df	Chlorophyll	Chlorophyll	Chlorophyll	Chlorophyll
		at DAP57	at DAP67	at DAP88	at DAP103
Season	1	4.63	39.86	182.52**	243.66**
Replicate(season)	4	6.14	1.85	34.63	5.31
Irrigation	3	145.42**	133.40**	49.89*	44.39***
Season×irrigation	3	6.82	3.39	117.24***	87.34***
Replicate×irrigation(season) (Ea)	12	17.73	15.47	9.23	3.27
Nitrogen	3	508.24***	408.50***	402.29***	176.86***
Season×nitrogen	3	2.63	1.01	10.28	0.78
Irrigation×nitrogen	9	31.67***	8.39	7.31	7.75
Season×irrigation×nitrogen	9	1.82	1.07	6.15	3.73
Error (Eb)	48	6.19	4.30	3.61	5.96
R ²		0.90	0.91	0.93	0.83
CVa		9.99	10.85	9.65	6.24
CVb		5.90	5.72	6.03	8.42

Ea = error of the main plots, Ea = error of the subplots, CVa = coefficient of variation for the main plots, CVb = coefficient of variation for the subplots. ‘***’, ‘**’ and ‘*’ are significance codes at 0.001, 0.01 and 0.05, respectively.

6.5.2 Effects of N rates and irrigation regimes on NDVI values at different growth stages of potato

Irrigation and N significantly affected NDVI values collected with GreenSeeker at all growth stages of potato, where NDVI values increased with irrigation and N amount. Irrigation×nitrogen also influenced NDVI values at DAP57 ($P < 0.001$) and DAP67 ($P < 0.05$) (Table 6.2). The treatment means of NDVI values of potato across irrigation regimes varied from 0.581 to 0.661, 0.706 to 0.797, 0.812 to 0.868 and 0.870 to 0.905 at DAP57, DAP67, DAP88 and DAP103, respectively (Table 6.4). The treatment means across irrigation regimes significantly differed at all growth stages, and the highest values of NDVI were obtained under ETC100%. This implied that NDVI increased with irrigation amount up to ETC100% at all potato growth stages. It was observed that there was a significant increase in NDVI with N dosage at all potato growth stages. The NDVI values across N rates respectively ranged from

0.568 to 0.682, 0.700 to 0.783, 0.832 to 0.861 and 0.874 to 0.902 at DAP57, DAP67, DAP88 and DAP103. The highest and lowest values of NDVI across N rates were found with N3 and N0, respectively, throughout the crop cycle.

For the interaction effect at DAP57, the maximum values of NDVI, 0.725 and 0.807 at DAP57 and DAP67, respectively, were found under ETC85% with N3. The lowest NDVI values, 0.530 and 0.667 at DAP57 and DAP67, were obtained under ETC50% with N0 and ETC75% with N0, respectively. The significant effect of N for NDVI values collected with GreenSeeker at all crop growth stages showed that NDVI value responses were more due to N rates. Saravia *et al.* (2016) also observed a significant effect of irrigation regimes on NDVI values calculated from a reflectometer SpectroSense2+ (Skye Instruments Inc., Llandrindod Wells, UK), while the interaction effect was only significant at the late stage of potato. Bijay and Ali (2020) also revealed that NDVI values collected with GreenSeeker responded well to N rates.

Table 6.2: Mean squares of potato NDVI collected with GreenSeeker at different stages of potato

Source of variation	df	NDVI at	NDVI2	atNDVI3	atNDVI4	at
		DAP57	DAP67	AP88	DAP103	
Season	1	0.0005	0.0021	0.0013	0.0019*	
Replicate(season)	4	0.0064	0.0021	0.0003	0.0017	
Irrigation	3	0.0246***	0.0347**	0.0041	0.0031**	
Season×irrigation	3	0.0053*	0.0072	0.0060*	0.0009	
Replicate×irrigation(season) (Ea)	12	0.0012	0.0056	0.0013	0.0003	
Nitrogen	3	0.0498***	0.0321***	0.0032*	0.0035**	
Season×nitrogen	3	0.0023	0.0003	0.0001	0.0004	
Irrigation×nitrogen	9	0.0129**	0.0044*	0.0008	0.0006	
Season×irrigation×nitrogen	9	0.0028	0.0024	0.0002	0.0005	
Error (Eb)	48	0.0045	0.0016	0.0011	0.0010	
R ²		0.6719	0.8286	0.5614	0.5628	
CVa		5.5600	10.0718	4.2256	1.9910	
CVb		10.7568	5.3485	3.9252	3.0970	

Ea = error of the main plots, Ea = error of the subplots, CVa = coefficient of variation for the main plots, CVb = coefficient of variation for the subplots. ‘***’, ‘**’ and ‘*’ are significance codes at 0.001, 0.01 and 0.05, respectively.

6.5.3 Effects of N and irrigation regimes on % N leaf content at different growth stages of potato

Application of N and irrigation water had a significant ($P < 0.001$) effect on % N leaf content at all growth stages of potato: DAP57 ($P < 0.05$), DAP67 ($P < 0.001$), DAP88 ($P < 0.001$) and DAP103 ($P < 0.001$) (Table 6.3). A significant effect of irrigation×nitrogen was observed at the late stages of the crop (DAP103). At all stages where plant leaf was sampled, it was observed that % N leaf content increased as the irrigation amount increased and the highest value of % N leaf content was found with ETC100% (Table 6.4). The % N leaf content significantly reduced as N level decreased at all growth stages of potato. Means of % N leaf content under different N treatments ranged from 3.645 to 5.326, 2.440 to 4.111, 1.262 to 2.884 and 0.416 to 1.481 at DAP57, DAP67, DAP88 and DAP103, respectively. The lowest % N leaf content was obtained with N0 at all crop growth stages. The significant effect of N and irrigation on % N leaf content at all crop growth stages showed that % N leaf content was more due to a single effect than the interaction between the two factors.

Across irrigation treatment, the highest % N leaf content obtained under ETC100% at DAP57 and DAP67 can be attributed to the ability of the crop to uptake applied N in well-irrigated plots. This disagreed with Shahnazari *et al.* (2008), who indicated that the leaf N content of potato showed a significant increase as the water stress became more severe. The findings are in line with the previous reports that showed that an increment in N rate generally increases % N leaf content in various crops (Elsaid & Silva, 2017; Majić *et al.*, 2008; Németh *et al.*, 2007; Pradhan *et al.*, 2018; Zheng *et al.*, 2015). Previous studies also reported this trend (Elsaid & Silva, 2017; Pradhan *et al.*, 2018; Zaeen, 2020). Increasing the N rate in muskmelon grown under ETC100% and ETC75% in Vertic Calciorthid aridisol linearly increases the % N leaf content (Kirnak *et al.*, 2005). The same trend was also obtained by Zhang *et al.* (2017a) in rice.

Table 6.3: Mean squares of % N leaf content at different stages of potato

Source of variation	df	% N leaf at			
		DAP57	DAP67	DAP88	DAP103
Season	1	0.55	0.50	0.50	0.02
Replicate(season)	4	0.65	0.81	0.98	0.40
Irrigation	3	0.95*	1.83***	2.32***	3.65***
Season×irrigation	3	0.47	0.41	0.16	0.15
Replicate×irrigation(season) (Ea)	12	0.19	0.17	0.17	0.11
Nitrogen	3	12.65*	12.55***	11.96***	4.96***
Season×nitrogen	3	0.12	0.09	0.03	0.04
Irrigation×nitrogen	9	0.30	0.29	0.26	0.55***
Season×irrigation×nitrogen	9	0.12	0.12	0.13	0.04
Error (Eb)	48	0.22	0.24	0.20	0.12
R ²		0.83	0.82	0.84	0.85
CVa		9.44	12.08	18.63	34.78
CVb		10.15	14.50	20.47	19.20

Ea = error of the main plots, Ea = error of the subplots, CVa = coefficient of variation for the main plots, CVb = coefficient of variation for the subplots. '***', '**' and '*' are significance codes at 0.001, 0.01 and 0.05, respectively.

Table 6.4: Treatment means of leaf chlorophyll content, NDVI values and % N leaf content

Irrigation regime	Leaf chlorophyll content				NDVI values				% N leaf content				
	DAP57	DAP67	DAP88	DAP103	DAP57	DAP67	DAP88	DAP103	DAP57	DAP67	DAP88	DAP103	
ETC100%	40.366	34.740	29.509	27.140	0.662	0.797	0.868	0.905	4.918	3.824	1.753	1.631	
ETC85%	45.778	39.766	32.741	29.833	0.656	0.747	0.866	0.898	4.571	3.321	2.368	1.318	
ETC75%	42.732	35.990	32.667	29.023	0.630	0.732	0.838	0.890	4.491	3.241	2.371	1.276	
ETC50%	40.723	34.767	31.686	30.171	0.581	0.706	0.812	0.870	4.504	3.254	2.382	1.226	
Nitrogen													
N0	36.651	31.092	26.396	25.582	0.568	0.700	0.832	0.874	3.645	2.440	1.262	0.416	
N1	41.065	35.767	30.704	28.438	0.627	0.733	0.850	0.880	4.577	3.356	2.203	0.882	
N2	43.373	37.337	32.742	29.889	0.631	0.766	0.852	0.888	4.936	3.733	2.525	1.481	
N3	47.779	41.066	36.461	32.257	0.682	0.783	0.861	0.902	5.326	4.111	2.884	1.481	
Irrigation×nitrogen													
ETC100%	N0	33.493	29.040	24.880	23.857	0.667	0.798	0.828	0.883	4.160	3.092	0.978	0.315
ETC100%	N1	35.747	32.590	27.088	25.257	0.650	0.795	0.843	0.885	5.098	3.963	1.963	0.518
ETC100%	N2	41.657	35.547	30.203	27.388	0.608	0.793	0.840	0.887	4.983	3.920	1.865	0.647
ETC100%	N3	50.468	41.782	35.863	32.058	0.642	0.800	0.842	0.887	5.430	4.320	2.207	0.443
ETC50%	N0	36.277	30.500	26.417	27.084	0.530	0.660	0.839	0.864	3.391	2.141	1.271	0.487
ETC50%	N1	40.942	34.930	32.130	30.072	0.548	0.682	0.853	0.865	4.563	3.313	2.443	1.163
ETC50%	N2	41.870	35.858	32.895	30.478	0.583	0.732	0.858	0.858	4.747	3.497	2.627	1.347
ETC50%	N3	43.820	37.806	35.320	33.088	0.662	0.750	0.860	0.892	5.300	4.050	3.180	1.900
ETC75%	N0	37.192	31.180	26.403	25.752	0.533	0.667	0.803	0.870	3.607	2.357	1.487	0.480
ETC75%	N1	41.698	35.685	32.617	27.735	0.630	0.713	0.845	0.880	4.237	2.987	2.117	0.837
ETC75%	N2	42.837	36.825	34.102	30.448	0.657	0.778	0.835	0.897	4.933	3.683	2.813	1.367
ETC75%	N3	46.280	40.268	37.547	32.155	0.698	0.768	0.870	0.915	5.187	3.937	3.067	1.620
ETC85%	N0	39.597	33.587	27.832	25.535	0.543	0.678	0.857	0.880	3.453	2.203	1.333	0.398
ETC85%	N1	45.875	39.863	30.980	30.688	0.680	0.742	0.860	0.888	4.410	3.160	2.290	1.010
ETC85%	N2	47.130	41.118	33.767	31.242	0.677	0.762	0.873	0.910	5.080	3.830	2.793	1.563
ETC85%	N3	50.508	44.497	37.185	31.865	0.725	0.807	0.873	0.912	5.340	4.090	3.053	1.940

6.5.4 Fitting models

Analysis of variance conducted over time indicated that the growth stages significantly ($P < 0.001$) affected leaf chlorophyll, NDVI, and the % N content. It was also observed that irrigation×stage significantly ($P < 0.001$) affected leaf chlorophyll, NDVI and % N content. Nitrogen×stage also significantly affected the late-stage parameters except for % N content (Table 6.5). The % N leaf and potato leaf chlorophyll content decreased as the season continued, whereas the NDVI values increased as the season continued under all irrigation regimes (Fig. 6.1 a, b and c). The NDVI values tended not to increase after DAP103 of the crop. Since several factors (including water deficit, the growth stage of potato, irrigation×nitrogen, irrigation×stage and nitrogen×stage) significantly ($P < 0.001$) affected leaf chlorophyll, NDVI and % N content, fitting models between leaf chlorophyll, NDVI, % N leaf content and N rate were evaluated under different irrigation regimes at different growth stages of the crop at $P < 0.05$ (Table 6.6). Different fitting equations, including exponential, linear, and polygonal, were obtained under various irrigation regimes at different stages of the potato crop. This showed that farmers might choose the best fitting model according to water stress conditions and crop stages when using the leaf chlorophyll and NDVI values for N recommendation in potato. N prediction in potato production based on N supply using these models depends on different water stress conditions and potato crop stages. Different slopes were obtained at different growth stages of potato and under different irrigation regimes. This indicated that the increase in leaf chlorophyll, NDVI and % N content with an increment in N dosage did not follow the same trend under different irrigation regimes as well as different crop stages.

These results agreed with the previous studies that reported that after the vegetative stage, leaf chlorophyll content generally decreased as the season continued (Elsaid & Silva, 2017; Zheng *et al.*, 2015). The same trend was also obtained in cotton crop (Ballester *et al.*, 2017). These study findings also agreed with Minotti *et al.* (1994). In contrast, leaf chlorophyll content values collected with SPAD were reported to increase with crop growth of dianthus (*Dianthus chinensis* L.) (Basyouni *et al.*, 2016), chrysanthemum (Khoddamzadeh & Dunn, 2016), poinsettia (*Euphorbia pulcherrima* L.) (Basyouni *et al.*, 2015; Dunn *et al.*, 2018) and apple (*Malus sp. Mill.*) (Lee *et al.*, 2019). These different findings can be explained by the fact that chlorophyll data were collected on different plants. The different fitting models developed in this study can be useful for farmers and scientists based on different water stress conditions and crop stages. Ramírez *et al.* (2014) obtained the best-fitted equation for chlorophyll under PRD30.

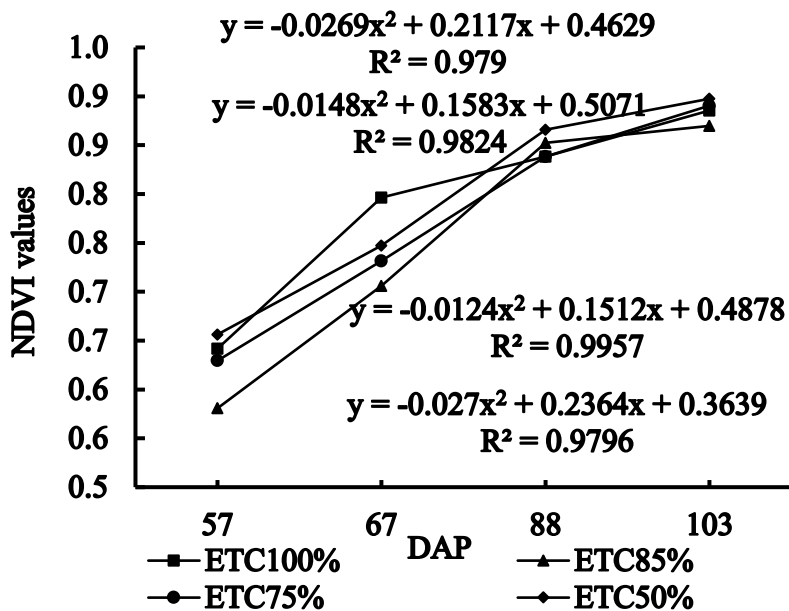
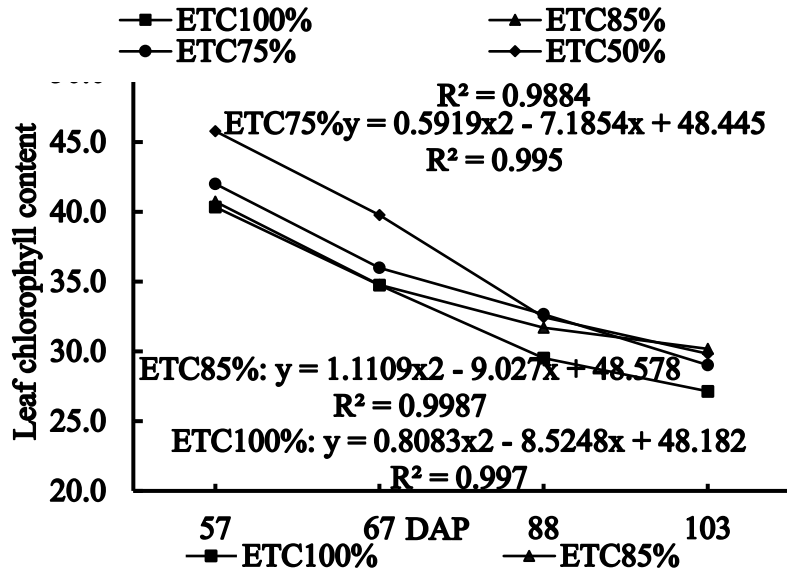
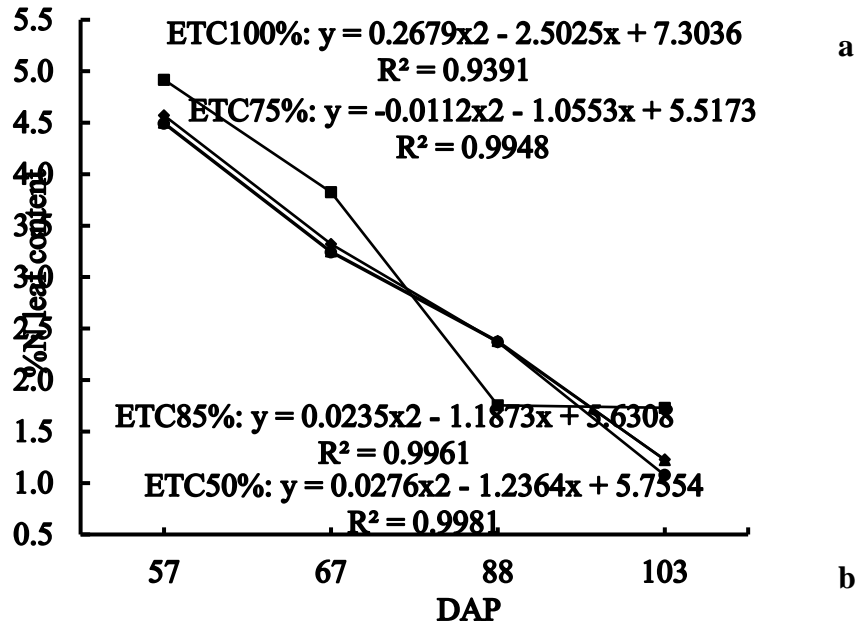


Figure 6.1: Variation of leaf chlorophyll, NDVI and % N leaf content values day after planting (DAP)

Table 6.5: Mean squares of potato leaf chlorophyll, NDVI and % N leaf content over time

Source of variation	df	Leaf chlorophyll	NDVI	% N leaf content
Season	1	353.1467***	0.0001	1.3090
Replicate(season)	4	28.8553	0.0044	2.5717
Irrigation	3	265.2971***	0.0322***	0.3987
Season×irrigation	3	94.2057**	0.0073	1.0017
Replicate×irrigation(season) (Ea)	12	11.4450	0.0024	0.4947
Nitrogen	3	1446.4923***	0.0645***	40.7495***
Season×nitrogen	3	4.5968	0.0016	0.2512
Irrigation×nitrogen	9	39.2459***	0.0102***	1.2826***
Season×irrigation×nitrogen	9	5.6107	0.0022	0.3236
Stage	3	3192.4631***	1.2823***	232.2337***
Season×stage	3	37.9126***	0.0019	0.0818
Irrigation×stage	9	36.8831***	0.0115***	2.7942***
Season×irrigation×stage	9	40.7212***	0.0039*	0.0622
Nitrogen×stage	9	15.4624**	0.0083***	0.4467
Season×nitrogen×stage	9	3.3871	0.0005	0.0103
Irrigation×nitrogen×stage	27	5.7014	0.0028	0.0390
Season×irrigat×nitrogen×stage	27	2.6261	0.0013	0.0277
Error (Eb)	240	6.0380	0.0020	0.1687
R2		0.9238	0.9083	0.9563
CVa		24.7115	8.7760	2.7893
CVb		7.0790	5.7605	14.7262

Ea = error of the main plots, Ea = error of the subplots, Cva = coefficient of variation for the main plots, CVb = coefficient of variation for the subplots. ‘***’, ‘**’ and ‘*’ are significance codes at 0.001, 0.01 and 0.05, respectively.

Table 6.6: Functions fitted to the responses of NDVI, leaf chlorophyll content and % N leaf content by N rate under different irrigation regimes and crop growth stages of potato grown in a mollic Andosol

	NDVI	Leaf chlorophyll content	% N leaf content
Vegetative growth stage			
ETC100%	$y = -2E-07x^2 + 5E-05x + 0.8829$, $R^2 = 0.9405$	$y = 0.0012x^2 - 0.0238x + 33.393$, $R^2 = 0.9955$	$y = -5E-05x^2 + 0.0152x + 4.1898$, $R^2 = 0.9206$
ETC85%	$y = -9E-06x^2 + 0.0025x + 0.5461$, $R^2 = 0.9591$	$y = 0.0825x + 40.002$, $R^2 = 0.9815$	$y = 0.0159x + 3.5115$, $R^2 = 0.9692$
ETC75%	$y = 0.0013x + 0.5408$, $R^2 = 0.98$	$y = 0.0681x + 37.233$, $R^2 = 0.9891$	$y = 3.6201e0.0029x$, $R^2 = 0.9641$
ETC50%	$y = 1E-05x^2 - 0.0003x + 0.5301$, $R^2 = 0.99$	$y = 0.0575x + 36.7$, $R^2 = 0.9697$	$y = -5E-05x^2 + 0.0204x + 3.4089$, $R^2 = 0.9871$
Tuber initiation growth stage			
ETC100%	$y = 1E-06x^2 - 0.0002x + 0.7983$, $R^2 = 0.8294$	$y = 28.41e0.0027x$, $R^2 = 0.9632$	$y = -4E-05x^2 + 0.0145x + 3.1156$, $R^2 = 0.9465$
ETC85%	$y = 0.6709e0.0012x$, $R^2 = 0.8566$	$y = 0.0805x + 33.992$, $R^2 = 0.9816$	$y = 0.0151x + 2.2615$, $R^2 = 0.9692$
ETC75%	$y = -4E-06x^2 + 0.0014x + 0.6635$, $R^2 = 0.8828$	$y = 0.0651x + 31.221$, $R^2 = 0.9892$	$y = 0.0121x + 2.3464$, $R^2 = 0.9634$
ETC50%	$y = 0.6553e0.001x$, $R^2 = 0.9208$	$y = 0.0557x + 30.875$, $R^2 = 0.974$	$y = -5E-05x^2 + 0.0204x + 2.1589$, $R^2 = 0.9871$
Tuber bulking growth stage			
ETC100%	$y = -2E-06x^2 + 0.0003x + 0.8284$, $R^2 = 0.906$	$y = 0.0007x^2 - 0.0014x + 24.866$, $R^2 = 0.9998$	$y = -7E-05x^2 + 0.0174x + 1.0048$, $R^2 = 0.935$
ETC85%	$y = 0.8054e0.0006x$, $R^2 = 0.8672$	$y = 0.072x + 27.398$, $R^2 = 0.9805$	$y = 0.0136x + 1.4119$, $R^2 = 0.9706$
ETC75%	$y = 0.8054e0.0006x$, $R^2 = 0.8672$	$y = 0.0845x + 26.752$, $R^2 = 0.9869$	$y = 0.0128x + 1.4764$, $R^2 = 0.9634$
ETC50%	$y = 0.0002x + 0.8408$, $R^2 = 0.9294$	$y = 0.0674x + 26.972$, $R^2 = 0.9592$	$y = 0.0134x + 1.3696$, $R^2 = 0.9696$
Maturation growth stage			
ETC100%	$y = -2E-07x^2 + 5E-05x + 0.8829$, $R^2 = 0.9405$	$y = 0.0006x^2 - 0.0123x + 23.866$, $R^2 = 0.9999$	$y = -5E-05x^2 + 0.0073x + 0.305$, $R^2 = 0.8653$
ETC85%	$y = 0.0003x + 0.8661$, $R^2 = 0.9339$	$y = -0.0005x^2 + 0.1087x + 25.584$, $R^2 = 0.9926$	$y = 0.0122x + 0.3745$, $R^2 = 0.9864$
ETC75%	$y = 0.0003x + 0.8661$, $R^2 = 0.9339$	$y = 25.547e0.0018x$, $R^2 = 0.969$	$y = 0.0092x + 0.4338$, $R^2 = 0.9553$
ETC50%	$y = 4E-06x^2 - 0.0004x + 0.8653$, $R^2 = 0.8192$	$y = 0.0442x + 27.083$, $R^2 = 0.9713$	$y = 0.0106x + 0.4837$, $R^2 = 0.9886$

6.5.5 In-season N assessment using leaf chlorophyll and NDVI

A significant correlation was observed between % N leaf content and leaf chlorophyll content measured with CM-100. In all irrigation treatments, the correlation coefficient between % N leaf content and leaf chlorophyll content ranged between 0.39 and 0.59 (Fig. 6.2). The highest correlation coefficient between % N leaf content and leaf chlorophyll content ($r = 0.59^{***}$) was obtained at DAP88 of the crop. A significant correlation was also observed between % N leaf content and NDVI values obtained using a GreenSeeker sensor at DAP57 DAP67. The correlation coefficients between % N leaf content and NDVI values in all irrigation treatments ranged between 0.28 and 0.57. The highest correlation coefficient between % N leaf content and leaf chlorophyll content ($r = 0.57^{***}$) was obtained at DAP67 of the crop (Fig. 6.3). Contrary to this finding, Johnkutty and Palaniappan (1995) found a highly significant correlation between leaf chlorophyll and plant N concentration at all stages of rice. Zhang *et al.* (2017a) also reported a high positive correlation between leaf chlorophyll content and leaf N concentration. Gianquinto *et al.* (2004) obtained a strong correlation between leaf chlorophyll and leaf N concentration of potato. However, the authors did not specify which stage of the crop this correlation was obtained. Chlorophyll content measured using SPAD-502 had a significant correlation with leaf N content of poinsettia (Basyouni *et al.*, 2015; Dunn *et al.*, 2018), apple (Lee *et al.*, 2019), summer maize (Zhao *et al.*, 2018) and potato crop (Fernandes *et al.*, 2021; Li *et al.*, 2012). This showed that CM-100 could be used to assess the in-season N status of potato grown in a mollic Andosol. However, the weak Pearson correlation obtained in this study can be explained by the combined data analyses from all irrigation treatments. Previous research reported that several factors such as plant cultivar, plant growth stage, leaf thickness, specific leaf weight, leaf position on the plant, water stress, soil type, measurement location on the leaf as well as the, solar radiation and other environmental stress factors significantly affect leaf chlorophyll content (Ata-Ul-Karim *et al.*, 2016; Dunn *et al.*, 2018; Lee *et al.*, 2019; Prost & Jeuffroy, 2007; Zhao *et al.*, 2016; Ziadi *et al.*, 2008). Feekes 6 stage of wheat was reported as the critical N stage of wheat (Zhang *et al.*, 2019) whereas tuber initiation and bulking stages of potato were considered as the critical N period (Ojala *et al.*, 1990). Giletto and Echeverría (2013a) concluded that a chlorophyll meter reading can be used to assess N status at the vegetative growth stage of potato. Gianquinto *et al.* (2004) reported a strong relationship up to $r = 0.80$ between leaf N content and leaf chlorophyll content. The highest Pearson correlation coefficient, $r = 0.59^{***}$, obtained in this study can be explained by the fact that the data from all irrigation treatments were combined.

This study indicated that GreenSeeker should only be used at the early stages (vegetative and tuber initiation) of potato for in-season N assessment in a mollic Andosol since the correlation coefficients obtained at DAP88 and DAP103 were very weak. This recommendation is supported by the previous study that reported that % N leaf content significantly correlated with NDVI values collected in wheat (Fabbri *et al.*, 2020). NDVI measurement was reported to be a suitable method for in-season N management in rice (Yao *et al.*, 2014) and wheat (Ratanoo *et al.*, 2016; Ravier *et al.*, 2017). Rehman *et al.* (2019) found a strong relationship between NDVI values and N uptake and N concentration in rice. Other studies reported strong and weak correlations between N leaf content and NDVI values in rice (Gnyp *et al.*, 2014; Li *et al.*, 2018; Lu *et al.*, 2017). The relationships between % N leaf content and NDVI values recorded using a GreenSeeker sensor at the late stages of the crop were weak. The result of this study is in line with the earlier studies in which NDVI values from GreenSeeker reached saturation at the vegetative stage when assessing N status in wheat and maize (Chlingaryan *et al.*, 2018; Maresma *et al.*, 2016; Muñoz-Huerta *et al.*, 2013). This saturation of NDVI at late stages of various crops (rice, maize and wheat) was well known and discussed (Chlingaryan *et al.*, 2018; Maresma *et al.*, 2016; Muñoz-Huerta *et al.*, 2013).

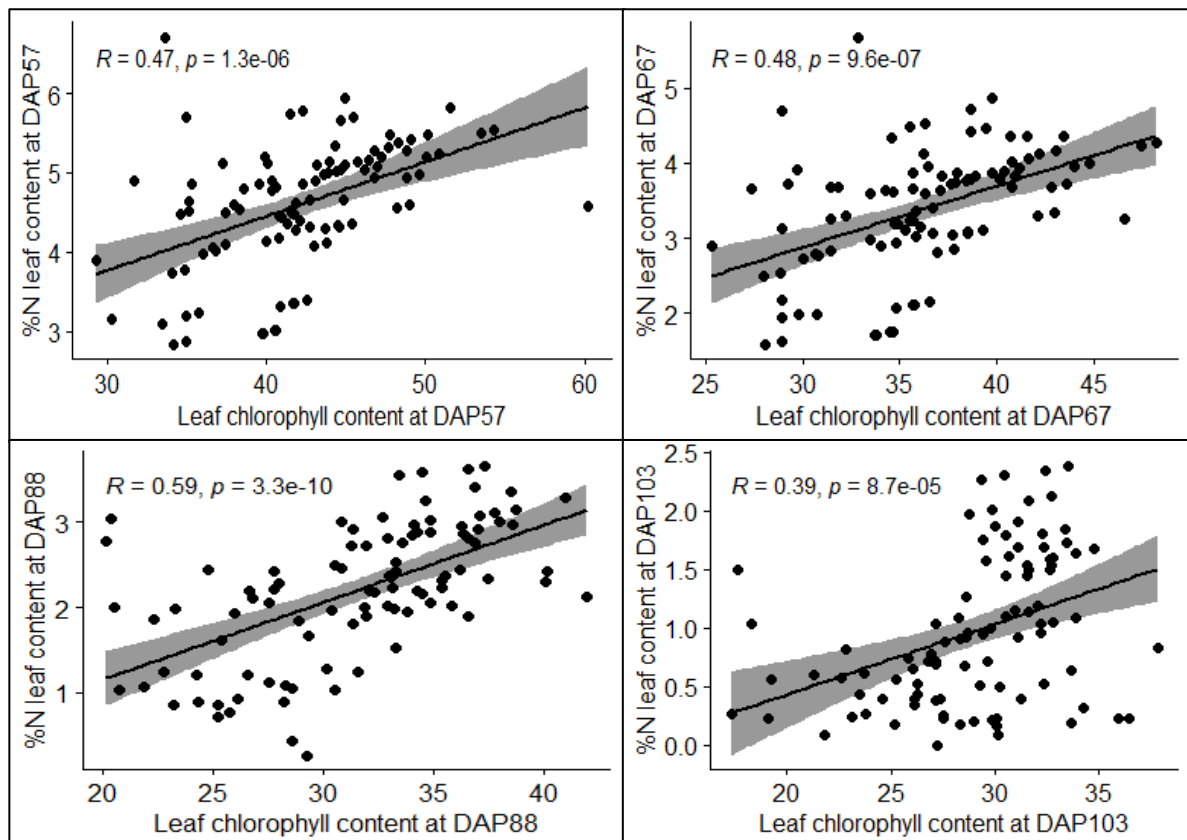


Figure 6.2: Relationship between % N leaf content and leaf chlorophyll content collected with CM-100 at different growth stages of potato

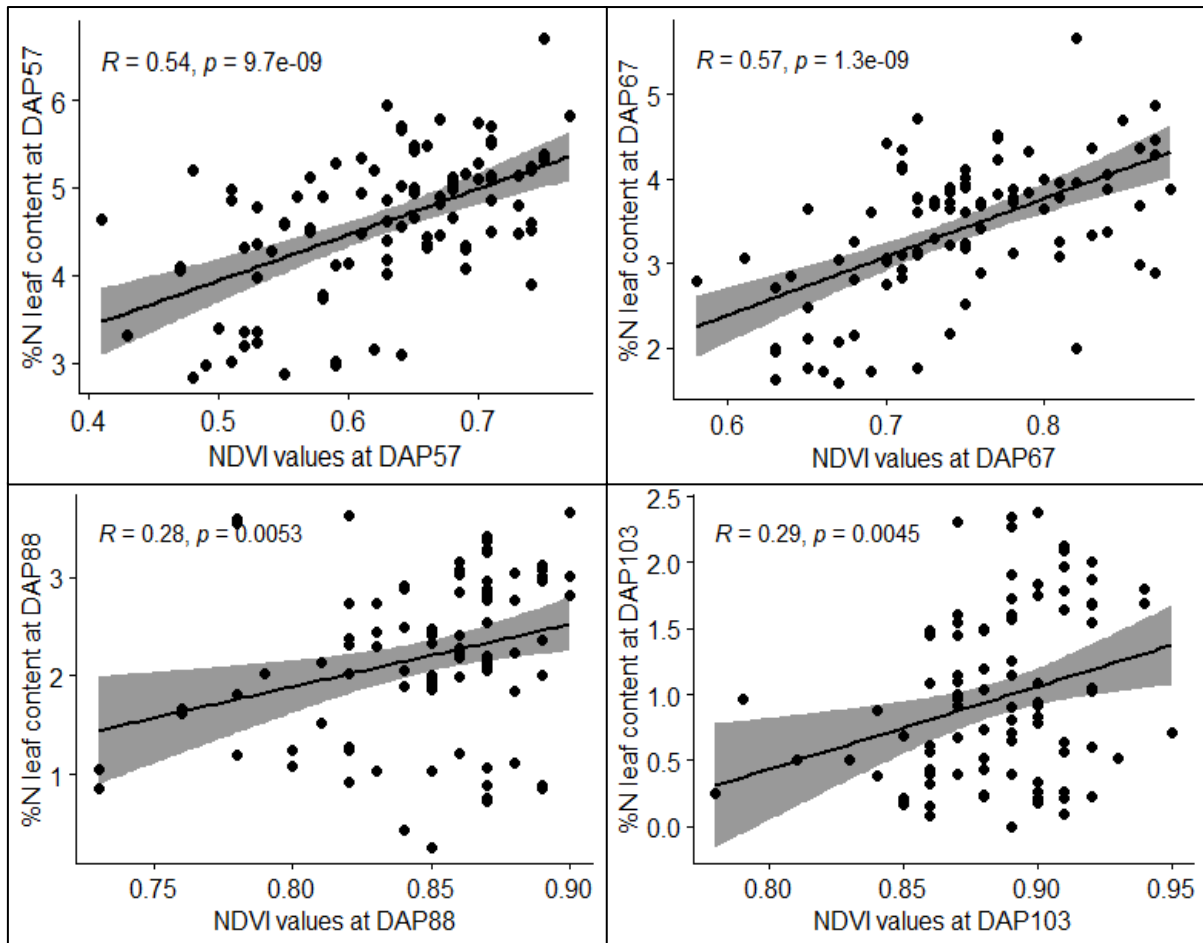


Figure 6.3: Relationship between % N leaf content and NDVI values collected with GreenSeeker at different growth stages of potato

6.5.6 In-season yield prediction using leaf chlorophyll and NDVI

A significant correlation was obtained between fresh potato tuber yield and % N leaf content throughout the season. It ranged between 0.33 and 0.81 where the highest values ($r = 0.81^{***}$ and $r = 0.80^{***}$) were found at DAP67 and DAP57, respectively (Fig. 6.4). This showed that a high % N leaf content at DAP67 and DAP57 can lead to high fresh tuber yield. Agricultural practices that increase % N leaf content are encouraged to be carried out at the vegetative and tuber initiation growth stages of the crop. The fresh potato tuber yield collected from different treatments showed a significant correlation with the leaf chlorophyll content throughout the growing season. The correlation coefficient ranged from 0.26 to 0.56, where the highest ($r = 0.56^{***}$) was obtained at DAP67 (Fig. 6.5). The Pearson correlation found between fresh potato tuber yield and NDVI was also significant at different stages of the crop. The correlation coefficient obtained varied between 0.22 and 0.62, with the highest ($r = 0.62^{***}$) value obtained at DAP57 (Fig. 6.6).

This study showed that direct assessment of leaf N in potato could be a good indicator to predict potato yield. However, direct in-season N assessment using the Kjeldahl digestion method can be complicated for the farmer. Therefore, this study found an alternative yield prediction using NDVI or leaf chlorophyll. This study suggested that NDVI and leaf chlorophyll can be used to predict potato tuber yield at vegetative and tuber initiation stages of potato. Earlier research found a highly significant correlation between tuber yield and potato leaf chlorophyll content values measured with SPAD (Güler, 2009; Majić *et al.*, 2008; Wilkinson *et al.*, 2019). A significant correlation was also reported between NDVI value and the yield of grain crops (Cao *et al.*, 2015; Lofton *et al.*, 2012; Zaeen, 2020). Lofton *et al.* (2012) faced challenges in sugarcane yield prediction using GreenSeeker due to a multi-year cropping cycle with a short growth period.

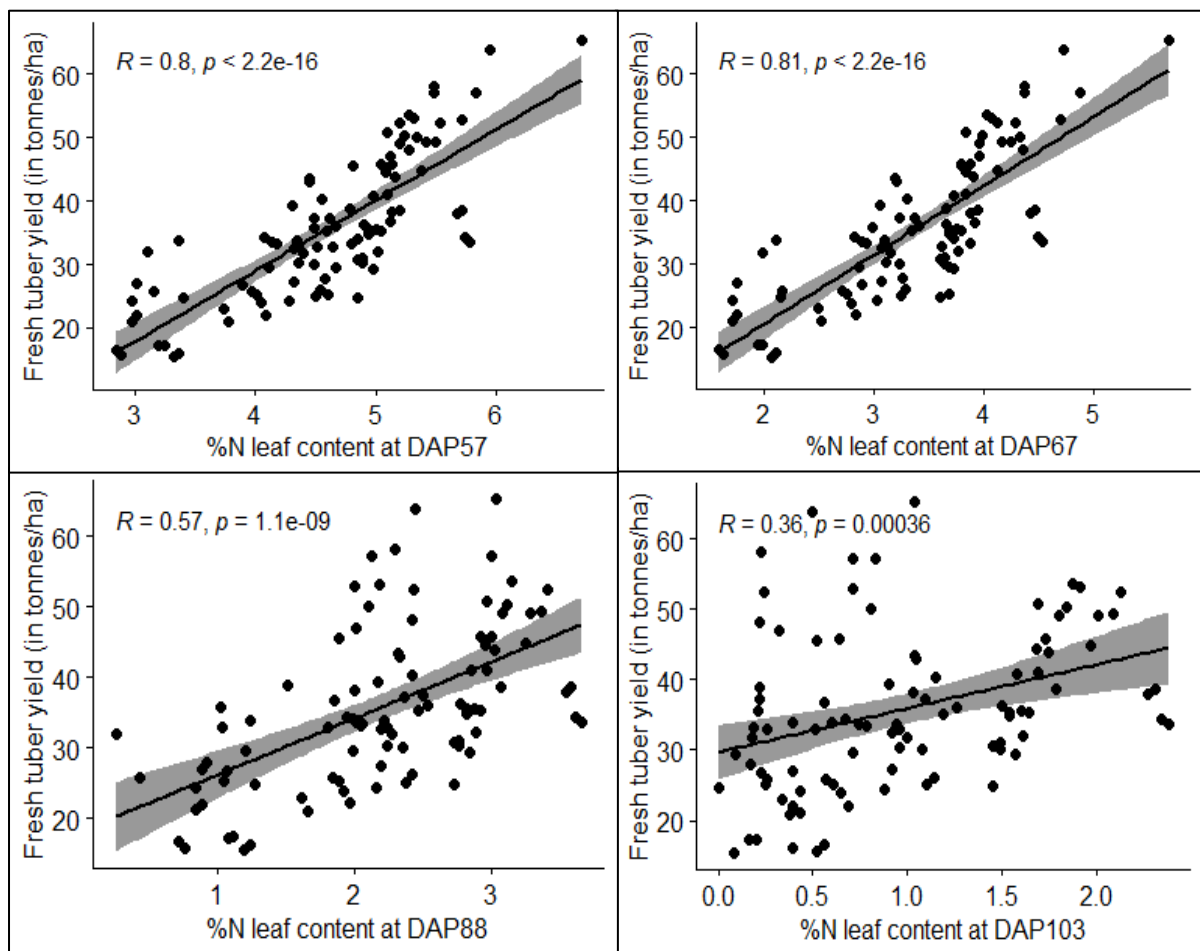


Figure 6.4: Relationship between fresh tuber yield and % N leaf content at different growth stages of potato

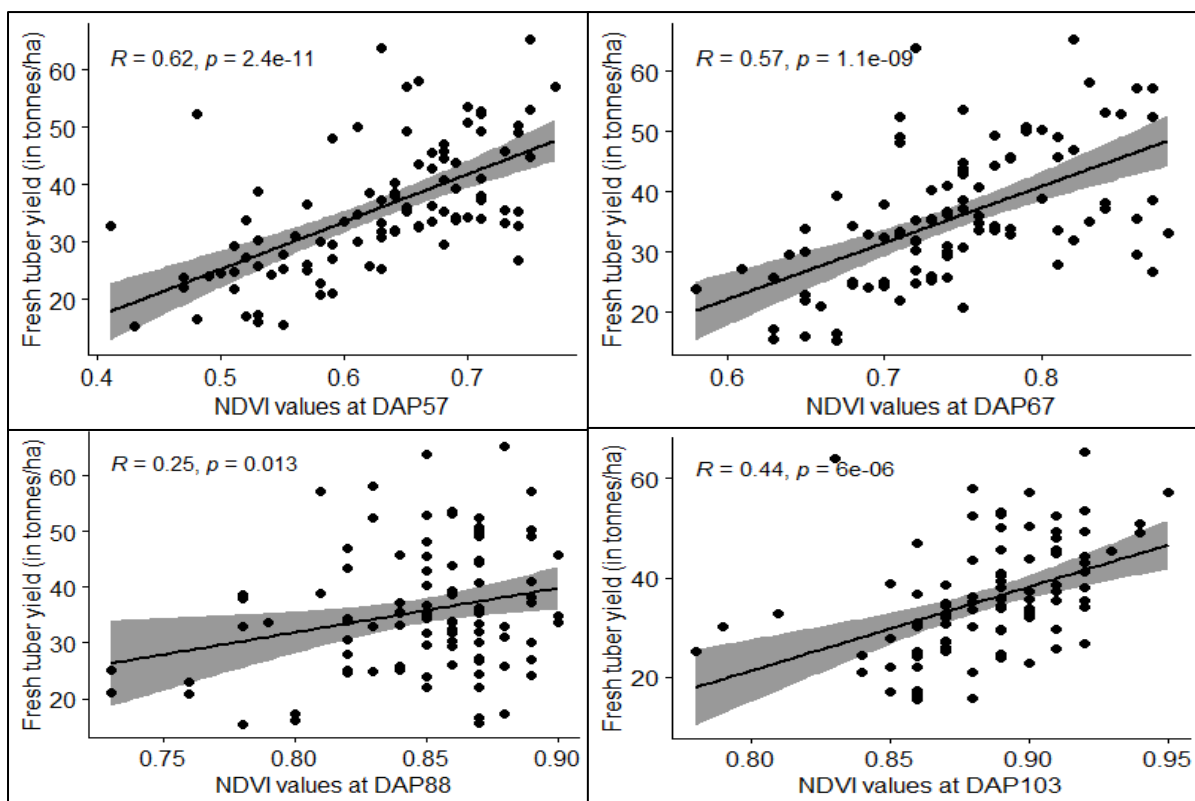


Figure 6.5: Relationship between fresh tuber yield and leaf chlorophyll at different growth stages of potato

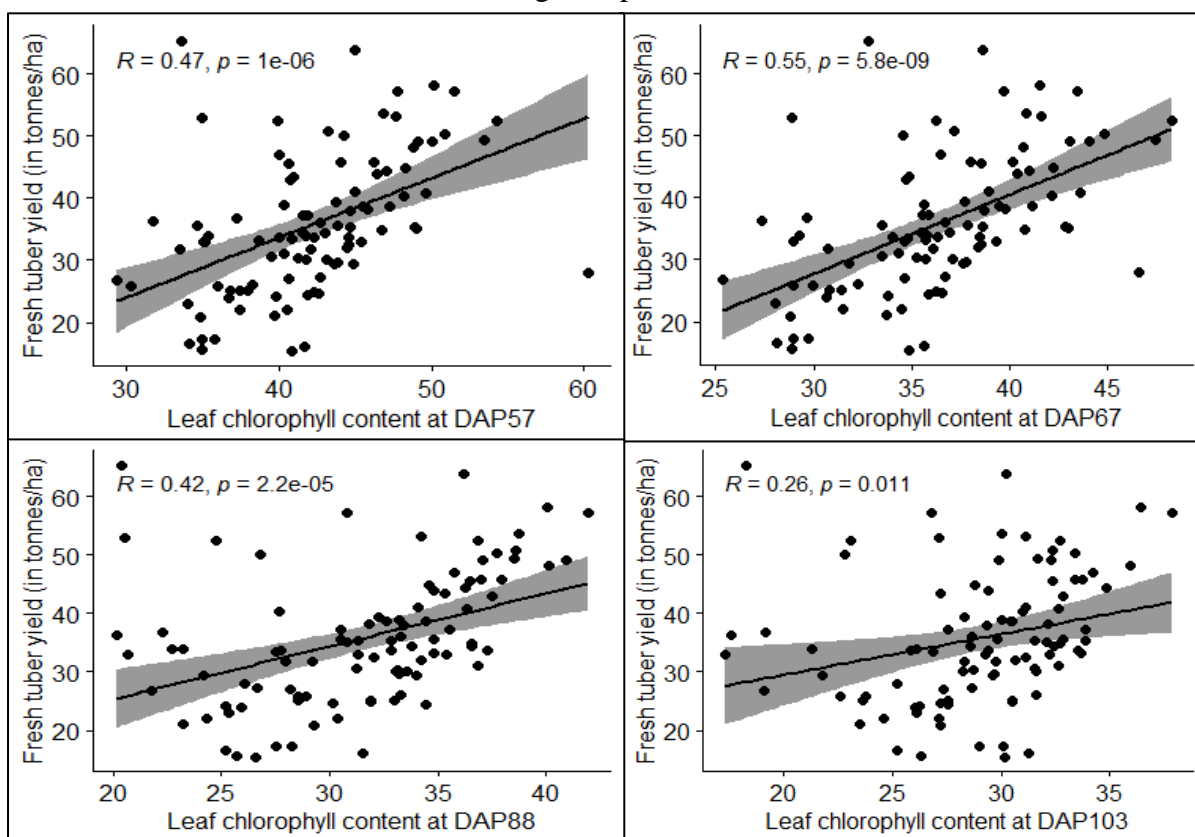


Figure 6.6: Relationship between fresh tuber yield and NDVI collected with GreenSeeker at different growth stages of potato

6.6 Conclusion

Nitrogen fertilization is an important factor in potato production. Due to its cost alongside environmental impacts, it requires proper management. These results showed that N fertilizer significantly interacted with leaf chlorophyll, NDVI and % N leaf content at all potato growth stages, where leaf chlorophyll content, NDVI values and % N leaf content increased with the N rate. This study also showed that leaf chlorophyll, NDVI and % N leaf of potato are affected by soil water content (irrigation regimes), crop growth stage, irrigation×nitrogen, irrigation×stage and nitrogen×stage. The study recommends using leaf chlorophyll, NDVI and % N leaf for in-season N recommendation and yield prediction at early crop growth stages. However, leaf chlorophyll and NDVI values might strongly correlate with the available soil moisture.

CHAPTER SEVEN

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1 General discussion

7.1.1 Effect of supplemental irrigation on yield, water use efficiency and nitrogen use efficiency of potato grown in a mollic Andosol

Irrigation and fertilization are two important components of food production, especially in dry areas with insufficient rainfall. The cumulative actual crop evapotranspiration (ET_a) was on average 253 mm and 370.68 mm for RF and FI, respectively. This showed a decrease in rainfall during the growing seasons. A reduction in seasonal rainfall was also reported by Waaswa *et al.* (2021), Kinyanjui (2019) and Muthoni *et al.* (2017). Potato ET_a was higher during the second season due to the high temperature and the low rainfall received than in the first season. This led to a high additional irrigation amount during the second season.

Potato plant height and number of branches per plant obtained under FI differ from the plant height and number of branches per plant observed under RF. In addition, plant height and number of branches per plant significantly increased with the N rate. This did not support the findings of Kassaye *et al.* (2020) and Darabad (2014), who indicated that an increase in irrigation amount did not increase plant height. These findings are in line with the previous research that reported an increment in potato plant height with an increase in irrigation amount applied (Farrag *et al.*, 2016; Gogoi *et al.*, 2020; Mansour & Abu El-Fotoh, 2018; Metwaly & El-Shatoury, 2017; Zhang *et al.*, 2017b). This difference in conclusions can be related to the stage at which the plant height was collected from the crop as well as the soil type and crop genotype utilized in this study. This study agreed with the previous research that indicated that potato plant height increased with an increment in the amount of N applied (Godebo & Belay, 2020; Setu & Mitiku, 2020; Tolessa *et al.*, 2017). An application of N generally increased potato plant height compared to an unfertilized plot (Godebo & Belay, 2020; Kahsay, 2019; Negero, 2017; Shunka *et al.*, 2017; Yadav *et al.*, 2017).

It was observed that total potato yield and marketable yield obtained with the different N rates were higher under FI. This study indicated that total fresh tuber yield significantly increased with an increase in the amount of N applied under FI compared to RF. It was also reported that an application of supplemental irrigation of 90 mm significantly increased potato yield compared to rain-fed production (Bélanger *et al.*, 2000; Qin *et al.*, 2013). It was found that the rainfall water received during the growing seasons was not enough to cover the potato crop water demand of the growing area. This indicated that supplemental irrigation is very important to maximize potato yield in the growing areas. Begum *et al.* (2018) indicated that

supplemental irrigation is very important for potato production in areas with a high drought frequency. This study indicated that an increase in N applied significantly increased the WUE and IWUE of potato. This is in line with the previous research (Li *et al.*, 2012; Najm *et al.*, 2012; Razzaghi *et al.*, 2012).

7.1.2 Effects of nitrogen and irrigation regimes on growth and yield of apical rooted cuttings of potato grown in a mollic Andosol

Potato is a water-demanding crop, and slight water stress at any stage might negatively affect its yield and quality. The total water demand for potato varied from 350 to 800 mm for various climates and environments (Tolessa, 2019). In this study, the cumulative actual crop evapotranspiration (ET_a) in a mollic Andosol was on average 2001.4, 302.1, 342.4 and 402.8 mm under ETC50%, ETC75%, ETC85% and ETC100% respectively. Potato water demand varies with soil types. Potato water demand was estimated at 413.2 and 362.1 mm in loam and clay soil, respectively (Katerji *et al.*, 2011). In a mollic Andosol, it was found that potato height and the number of branches did not increase with irrigation amount. Elhani *et al.* (2019) also indicated the same trend. However, several studies have reported an increase in potato plant height with an increment in irrigation amount (Darabad, 2014; Farrag *et al.*, 2016). It was also reported that potato plant height generally increased with N increment, as reported in this study (Jafari-Jood *et al.*, 2013; Kahsay, 2019; Setu & Mitiku, 2020).

This study found that potato total tuber yield and marketable yield in a mollic Andosol were generally responsible for the irrigation×nitrogen effect rather than the effect of a single factor. The highest potato total tuber yield, 58.29 t ha⁻¹, and marketable potato yield, 54.21 t ha⁻¹, in a mollic Andosol were observed under ETC100% with an application of 130 kg N ha⁻¹. The reduction in total tuber yield due to progressive water stress averaged 8.62, 15.90 and 35.57%, respectively, under ETC85%, ETC75% and ETC50% while a reduction of irrigation amount by 50% reduced marketable potato yield by about 40.31%. This indicated that irrigation and N-fertilization are some of the key factors that control potato yield and quality in a mollic Andosol. Badr *et al.* (2012) also found a significant interaction effect of both factors on fresh potato tuber yield. This did not support the findings of Bohman *et al.* (2019) who reported that irrigation×nitrogen had no significant effect on potato yield and marketable tuber yield. This different conclusion can be related to the soil types and the environment where the experiment was conducted as well as the plant material. The harvest index (HI) of potato grown in a mollic Andosol was significantly affected by the interaction effect of both factors whereas the tuber

dry matter was only affected by N. The highest HI was obtained under ETC50% with 130 kg N ha⁻¹. This was due to the heavy biomass obtained from well-irrigated plots.

7.1.3 Effect of nitrogen rates and irrigation regimes on nitrogen use efficiency and water use efficiency of potato grown in a mollic Andosol

Potato WUE is a very important parameter for the profitability of irrigated potato. A high WUE while achieving the highest yield has always been the purpose of researchers in various crops. In a mollic Andosol, it was observed that potato WUE reduced with an increment in irrigation amount. However, it increased with the N rate. The maximum potato WUE was obtained at ETC50% with an application of 130 kg N ha⁻¹ in three splits. This trend was also reported by a previous study (Elhani *et al.*, 2019). The highest potato WUE, 17.5 kg m⁻³, obtained under ETC50% can be due to the less irrigation amount applied. It was also reported that potato is one of the high WUE crops (Hoekstra, 2008). However, a study conducted by Tolessa *et al.* (2016) in clay soil showed that irrigation did not affect potato WUE. This can be attributed to the fact that clay soils have a high water retention capacity.

Nitrogen is one of the key factors in potato production due to its role in the biological process, especially at growth stages (Ospina *et al.*, 2014). Potato NUE is among the key parameters to evaluate the profitability of potato. It was observed in this study that potato NUE increased with the irrigation amount applied. This can be explained by the fact that soil water affects nutrient transport to the root surface in the water flux created by transpiration (mass flow) (Smethurst, 2004) and water uptake by roots considerably enhances root N acquisition by mass flow (McMurtrie & Näsholm, 2018). Water stress also reduces N uptake as a result of the decreased water uptake and transpiration rate (Koch *et al.*, 2020). This study also showed that further N application of N above 90 kg N ha⁻¹ might not improve the NUE of potato grown in a mollic Andosol. Potato NUE depends on the soil types and potato genotypes (Maresma *et al.*, 2016). Some earlier studies reported the highest potato NUE when applying 100 kg N ha⁻¹ (Ierna & Mauromicale, 2019), 120 kg N ha⁻¹ (Maltas *et al.*, 2018) and 180 kg N ha⁻¹ (Ospina *et al.*, 2014). The correlation between NUE and WUE obtained in this study was weak but significant. Excessive irrigation reduced WUE and increased NUE, whereas high N dosage increased WUE and decreased NUE of potato grown in a mollic Andosol. This needs to be considered when looking at WUE and NUE of potato grown in a mollic Andosol.

7.1.4 Possibility of the use of leaf chlorophyll content and normalized difference vegetation index for in-season N assessment and potato yield prediction

It was observed that potato leaf chlorophyll and % N in leaf content decreased while the NDVI values increased as the season continued. After the vegetative stage, leaf chlorophyll content generally reduced as the season continued (Elsaid & Silva, 2017; Zheng *et al.*, 2015). Ballester *et al.* (2017) also reported the same trend in cotton (*Gossypium hirsutum*). This study showed that potato leaf chlorophyll collected with CM-100, NDVI recorded with GreenSeeker sensor and % N leaf content were more responsive to N than irrigation. The % N leaf content generally increases with the amount of N applied (Elsaid & Silva, 2017; Majić *et al.*, 2008; Németh *et al.*, 2007; Zheng *et al.*, 2015). It was also observed that potato leaf chlorophyll and NDVI were also significantly affected by irrigation and the interaction of both factors at vegetative and tuber initiation stages of potato grown in a mollic Andosol.

In-season N assessment is the method that matches potato N needs with N supply. This has become the purpose of many studies due to the cost of N fertilizer and its environmental impacts when it is inappropriately applied. This study found the highest correlation coefficients between % N leaf content and leaf chlorophyll at DAP88 ($r = 0.59^{***}$), followed by DAP67 ($r = 0.48^{***}$) and DAP57 ($r = 0.47^{***}$). However, the highest correlation coefficients between % N leaf content and NDVI values were obtained at DAP67 ($r = 0.57^{***}$) and DAP57 ($r = 0.54^{***}$). Gianquinto *et al.* (2004) reported a strong relationship up to $r = 0.80$ between leaf N content and leaf chlorophyll content of potato. NDVI values collected in this study reached saturation at the vegetative stage of the crop. This is in line with the earlier studies in which NDVI values from GreenSeeker reached saturation at the vegetative stage when measuring N status in wheat and maize (Chlingaryan *et al.*, 2018; Maresma *et al.*, 2016; Muñoz-Huerta *et al.*, 2013). As observed, leaf chlorophyll can be used for an in-season N status determination at vegetative, tuber initiation and tuber bulking stages of potato. However, NDVI values can only be used for N management at potato's vegetative and tuber initiation stages. Leaf chlorophyll content values taken with SPAD and % leaf N content showed a significant Pearson correlation at various stages of potato crop (Fernandes *et al.*, 2021; Li *et al.*, 2012). Leaf chlorophyll and NDVI can be used to assess N in potato production. However, the correlation coefficients obtained are not strong and this can be related to the irrigation effect and the interaction effect of both factors. This indicated that water stress conditions should be considered when taking these measurements. This study also developed several fitted models based on the crop stages as well as the water stress conditions. The findings of this study also suggested that the leaf chlorophyll and NDVI can be used to predict potato tuber yield at

vegetative and tuber initiation stages of potato. Earlier research found a highly significant correlation coefficient between tuber yield and leaf chlorophyll content values measured with SPAD (Güler, 2009; Majić *et al.*, 2008; Wilkinson *et al.*, 2019). A significant correlation was also reported between NDVI values and the yield of grain crops (Cao *et al.*, 2015; Lofton *et al.*, 2012; Zaeen, 2020). The NDVI values recorded using GreenSeeker were successfully used as yield and biomass indicators in the winter oilseed rape crop (Louvieaux *et al.*, 2020).

7.2 Conclusions and recommendations

7.2.1 Conclusions

- (i) A high tuber yield of 62.12 t ha⁻¹ can be achieved in Kenya when water deficits of the growing season are eliminated with supplemental irrigation and an application of 130 kg N ha⁻¹. The NUE consistently increases with the increase in N rate up to 90 kg N ha⁻¹ in the two irrigation treatments in the field.
- (ii) The period between tuber initiation and tuber bulking stages of potato forms the critical stage at which a slight water deficit can negatively affect the tuber yield. The cumulative actual potato crop evapotranspiration (ET_a) in a mollic Andosol is on average 2001.4, 302.1, 342.4 and 402.8 mm under ETC50%, ETC75%, ETC85% and ETC100%, respectively. A decrease in N and irrigation amount applied in a mollic Andosol significantly reduces total tuber yield and marketable yield. Potato grown under full irrigation (ETC100%) with an application of 130 kg N ha⁻¹ produced the highest potato tuber yield, 58.28 t ha⁻¹, and marketable tuber yield, 54.21 t ha⁻¹.
- (iii) For potato grown in a mollic Andosol, a maximum irrigation amount reduces WUE and increases NUE, whereas high N dosage increases WUE and decreases NUE. The highest NUE of potato grown in a mollic Andosol can be obtained with an application of 90 kg N ha⁻¹.
- (iv) The % N leaf and leaf chlorophyll of potato decrease as the season continued, whereas the NDVI values increase as the season continued under all irrigation regimes. A significant correlation exists between % N and both leaf chlorophyll and NDVI. A significant correlation exists between potato tuber yield and chlorophyll leaf content and NDVI values throughout the growing season. Irrigation regimes, potato growth stages, irrigation×nitrogen, irrigation×stage and nitrogen×stage interact with leaf chlorophyll and NDVI.

7.2.2 Recommendations

- (i) This study highlights the importance of introducing supplemental irrigation in the potato production area in Kenya. It recommends the replication of this study in other potato-growing regions of Kenya for general conclusions.
- (ii) This study recommends further research on different irrigation methods that lead to high tuber yield and marketable yield with high water use efficiency in a mollic Andosol.
- (iii) If maximizing NUE in a mollic Andosol is the purpose of the farmers, this study highlights that it is at the expense of potato WUE and yield should be looked at as the secondary target. Further research should explore other factors that interact with NUE and WUE in order to find the greatest compromise between NUE and WUE for an optimum tuber yield and quality and marketable tuber yield for potato grown in a mollic Andosol.
- (iv) This study indicated that leaf chlorophyll and NDV could be used at vegetative and tuber initiation stages for in-season N assessment and yield prediction in potato grown in a mollic Andosol. However, the fitted models developed in this study should be explored based on the crop growth stage and the water stress condition. The study recommends further studies to determine the thresholds of leaf chlorophyll and NDVI using various potato varieties in different locations.

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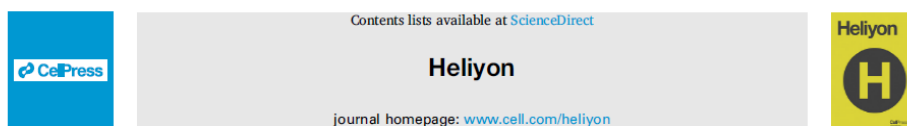
APPENDICES

Appendice A: Research permit NACOSTI

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Appendix B: Publications

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Research article

Performance of apical rooted cuttings of potato grown in Mollic Andosols under different nitrogen fertilization and irrigation regimes

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ARTICLE INFO

Keywords:
Water demand
Marketable tuber yield
Total tuber yield
Harvest index
Dry matter

ABSTRACT

Potato productivity (*Solanum tuberosum* L.) is generally influenced by several factors, including water and nitrogen (N), and potato requirement for these factors varies depending on the soil type and potato variety. This research aimed to determine the performance of apical rooted cuttings of potato grown in Mollic Andosols under different nitrogen fertilization and irrigation regimes. The treatments comprised 4 irrigation regimes of 100%, 85%, 75% and 50% of the crop evapotranspiration (ETC), where ETC100% was irrigated based on water depletion in the root zone two days after full irrigation, and 4 nitrogen rates of 0 (N0), 60 (N1), 90 (N2) and 130 kg ha⁻¹ (N3) applied in splits at 10 (40%), 30 (40%) and 50 (20%) days after planting. The results revealed that the water demand for apical rooted cuttings of potato (Eta) was on average 201.4, 302.1, 342.4 and 402.8 mm under ETC50%, ETC75%, ETC85% and ETC100%, respectively. It was observed that plant height and number of branches significantly ($P < 0.001$) varied under different N rates with the highest plant height (92.67 cm) and number of branches per potato plant (17) achieved when applying N3. Potato grown under full irrigation (ETC100%) with N3 produced the highest total potato tuber yield (58.28 t ha⁻¹) and marketable tuber yield (54.21 t ha⁻¹). The number of tubers per plant statistically reduced as the N deficit increased, with the maximum tuber number, 23, achieved under N3. It was observed that a significant Pearson correlation ($r = 0.7^{***}$) existed between tuber number and total tuber yield. The maximum harvest index (HI), 57.12 %, was obtained under ETC50% with N3, while the highest tuber dry matter, 30 %, was observed under N3. To achieve a high tuber yield from apical rooted cuttings of potato in Mollic Andosols, this study recommends an irrigation regime of ETC100% and a nitrogen rate of 130 kg ha⁻¹.

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Urban Agriculture & Regional Food Systems

ORIGINAL RESEARCH ARTICLE

Water use efficiency and nitrogen use efficiency of apical rooted cuttings of potato grown in a mollic Andosol

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Abstract

Water and nitrogen (N) are key interacting factors that control plant growth. The objective of the study was to determine the effect of N rates and drip irrigation regimes on water use efficiency (WUE) and N use efficiency (NUE) of apical rooted cuttings of potato (*Solanum tuberosum* L.) grown in a mollic Andosol. The treatments comprised four drip irrigation regimes of 50%, 75%, 85% and 100% of the crop evapotranspiration (ETC), where ETC100% was irrigated according to the soil water depletion 2 d after full irrigation and four N rates: 0 (N0), 60 (N1), 90 (N2) and 130 kg N ha⁻¹ (N3). The results showed that potato tuber yield, WUE, and NUE were significantly ($P < .001$) affected by irrigation regimes, N rates, and the interaction of both factors. The highest potato tuber yield, 58.29 Mg ha⁻¹, was obtained under ETC100% with N3, whereas the highest WUE, 17.5 kg m⁻³, was found under ETC50% with N3. The apical rooted cuttings of potato grown under ETC100% with N2 produced the maximum NUE, 208.30 kg kg⁻¹. The correlation coefficient ($r = 0.31$; $P < .01$) obtained between WUE and NUE was weak. It was also observed that an increase in irrigation amount decreased WUE and increased NUE, whereas a high N dosage increased WUE and decreased NUE of potato grown in a mollic Andosol. This study suggests that if the farmers aim to maximize NUE of apical rooted cuttings in a mollic Andosol, then they will do so at the expense of potato WUE, and yield will be looked at as a secondary factor.

1 | INTRODUCTION

Potato (*Solanum tuberosum* L.) is one of the major root and tuber food crops for many people around the world (FAO-STAT, 2017). Globally, 368 Tg of potato were produced in 2018 on an estimated area of 17.58 million ha (FAO-STAT, 2020). In Kenya, it is the second staple food and cash crop

(Satognon et al., 2021b; Waaswa et al., 2021b). This sector has been negatively impacted by climate change events that have lowered potato yield to 8.6 Mg ha⁻¹, which is below the global average yield of 21 Mg ha⁻¹ (Waaswa & Satognon, 2020; Waaswa et al., 2021a). These climate change events include pests and diseases, poor seed quality, poor water management, declining soil fertility, prolonged drought, low and high temperatures, and excessive radiation (Muthoni et al., 2017, 2021; Satognon et al., 2021a). To cope up with these climate change events, many technologies have been introduced in potato production in Kenya. These include apical

Abbreviations: NUE, nitrogen use efficiency; WUE, water use efficiency; ETC, crop evapotranspiration.

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RESEARCH

Open Access

Effects of supplemental irrigation on yield, water use efficiency and nitrogen use efficiency of potato grown in mollic Andosols



Felix Satognon^{*}, Seth F. O. Owido and Joyce J. Lelei

Background: Low soil fertility and reduced seasonal rainfall contribute to low potato (*Solanum tuberosum* L.) yield in Kenya. Nitrogen (N) deficiency is the major problem facing by the smallholder farmers of Kenya due to lack of fallow. Hence an introduction of supplemental irrigation with an adequate application of this nutrient could increase potato yield. The objective of this study was to determine the effects of supplemental irrigation and N-fertilisation on potato tuber yield, water use efficiency (WUE) and nitrogen use efficiency (NUE). The experiment was conducted in Nakuru County, Kenya for two seasons. The experimental soils are classified as mollic Andosols. The treatments comprised two irrigation treatments of full supplemental irrigation (FI) and rainfed production (RF) and four N levels of four N levels of 0 (N0), 60 (N1), 90 (N2) and 130 kg N/ha (N3).

Results: The results showed that total tuber yield, marketable tuber yield and NUE were significantly ($P < 0.001$) affected by irrigation \times N-fertilisation while WUE was only affected ($P < 0.001$) by N-fertilisation. The highest total tuber yield, 58.28 tonnes/hectare (t/ha), was recorded under FI combined with N3. Treatment FI significantly increased marketable tuber yield by approximately 125.58% in all N treatments compared to RF. The highest NUE of potato (236.44 kg/kg of N) was obtained under FI combined with N3 but not significantly different from the NUE of potato obtained under FI with N2. N-fertilisation N3 produced the highest WUE of 14.24 kg/m³. Significant correlation was obtained between tuber yield and number of tubers/plant ($r = 0.75$, $P < 0.001$), NUE ($r = 0.95$, $P < 0.001$) and WUE ($r = 0.72$, $P < 0.001$).

Conclusion: High potato yield and marketable tuber yield can be achieved in mollic Andosols when water deficits of the growing season are eliminated with supplemental irrigation and an application of 130 kg N/ha.

Keywords: N-fertilisation, NUE, Potato, Supplemental irrigation, WUE, Yield

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ORIGINAL RESEARCH ARTICLE



Use of GreenSeeker and CM-100 as manual tools for nitrogen management and yield prediction in irrigated potato (*Solanum tuberosum*) production

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ABSTRACT

This study evaluated the possibility of the use of GreenSeeker sensor and CM-100 chlorophyll content meter for in-season N and yield prediction in order to promote timely split N application in potato production in Kenya. Four N-fertilization rates; N₀(0), N₁(60), N₂(90) and N₃ (130 kg N/ha) were laid out in a Randomized Complete Block Design (RCBD) in a Greenhouse for two seasons. The results showed that % N leaf content was significantly affected by N rates. The % N leaf content and potato leaf chlorophyll content decreased as the season continued whereas the Normalized Difference Vegetation Index (NDVI) increased as the season continued. CM-100 values were significantly correlated with % N leaf content at vegetative ($r = 0.86^{***}$) and tuber initiation ($r = 0.74^{**}$) growth stages of the crop whereas the NDVI values were only significantly correlated with % N leaf at tuber initiation ($r = 0.82^{***}$). A significant relationship was found between CM-100 values taken at different potato stages (end of vegetative, tuber initiation, bulking and maturation stages) and tuber yield ($r = 0.90^{***}$, 0.82^{**} , 0.47^* and 0.41^*). The NDVI values at end of vegetative growth, tuber initiation and maturation of potato were also significantly correlated with tuber yield ($r = 0.81^{***}$, 0.43^* and 0.54^*), except at bulking stage ($r = 0.33$). For efficient in-season N management and yield prediction, CM-100 and GreenSeeker are recommended at an early stage of the crop. Further research in the different potato growing areas in Kenya to establish the different thresholds at different potato growth stages is recommended.

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Appendice C: Statistical outputs

Field experiment

Class Level Information		
Class	Levels	Values
sea	2	1 2
rep	3	1 2 3
Irrigation	2	FI RF
Nitrogen	4	N0 N1 N2 N3

Number of Observations Read	48
Number of Observations Used	48

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	9205.928848	400.257776	43.95	<.0001
Error	24	218.595200	9.108133		
Corrected Total	47	9424.524048			

R-Square	Coeff Var	Root MSE	YIELD Mean
0.976806	9.568006	3.017968	31.54229

Source	DF	Type IV SS	Mean Square	F Value	Pr > F
sea	1	42.846302	42.846302	4.70	0.0402
rep(sea)	4	44.346783	11.086696	1.22	0.3296
Irrigation	1	5172.769252	5172.769252	567.93	<.0001
sea*Irrigation	1	74.127552	74.127552	8.14	0.0088
rep*Irrigation(sea)	4	21.431283	5.357821	0.59	0.6743
Nitrogen	3	3017.708123	1005.902708	110.44	<.0001
sea*Nitrogen	3	44.519273	14.839758	1.63	0.2089
Irrigation*Nitrogen	3	749.676923	249.892308	27.44	<.0001
sea*Irrigat*Nitrogen	3	38.503356	12.834452	1.41	0.2645

Tests of Hypotheses Using the Type IV MS for rep*Irrigation(sea) as an Error Term					
Source	DF	Type IV SS	Mean Square	F Value	Pr > F
Irrigation	1	5172.769252	5172.769252	965.46	<.0001
sea	1	42.846302	42.846302	8.00	0.0474
sea*Irrigation	1	74.127552	74.127552	13.84	0.0205

Class Level Information		
Class	Levels	Values
sea	2	1 2
rep	3	1 2 3
regimes	4	ETC100% ETC50% ETC75% ETC85%
nitro	4	N0 N1 N2 N3

Rain shelter experiment

Class Level Information		
Class	Levels	Values
sea	2	1 2
rep	3	1 2 3
regimes	4	ETC100% ETC50% ETC75% ETC85%
nitro	4	N0 N1 N2 N3

Number of Observations Read	96
Number of Observations Used	96

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	47	11624.30203	247.32558	37.20	<.0001
Error	48	319.10982	6.64812		
Corrected Total	95	11943.41185			

R-Square	Coeff Var	Root MSE	yield Mean
0.973282	7.218204	2.578395	35.72073

Source	DF	Type IV SS	Mean Square	F Value	Pr > F
sea	1	73.447509	73.447509	11.05	0.0017
rep(sea)	4	4.502296	1.125574	0.17	0.9530
Irrigation	3	2894.929186	964.976395	145.15	<.0001
sea*Irrigation	3	83.635995	27.878665	4.19	0.0103
rep*Irrigation(sea)	12	195.840688	16.320057	2.45	0.0138
Nitrogen	3	7697.254328	2565.751443	385.94	<.0001
sea*Nitrogen	3	4.572336	1.524112	0.23	0.8756
Irrigation*Nitrogen	9	530.148251	58.905361	8.86	<.0001
sea*Irrigat*Nitrogen	9	139.971443	15.552383	2.34	0.0282

Tests of Hypotheses Using the Type IV MS for rep*Irrigation(sea) as an Error Term					
Source	DF	Type IV SS	Mean Square	F Value	Pr > F
Irrigation	3	2894.929186	964.976395	59.13	<.0001
sea	1	73.447509	73.447509	4.50	0.0554
sea*Irrigation	3	83.635995	27.878665	1.71	0.2182

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	47	12012.33775	255.58165	38.06	<.0001
Error	48	322.36803	6.71600		
Corrected Total	95	12334.70578			

R-Square	Coeff Var	Root MSE	mark Mean
0.973865	8.358971	2.591525	31.00292

Source	DF	Type IV SS	Mean Square	F Value	Pr > F
sea	1	75.260417	75.260417	11.21	0.0016
rep(sea)	4	7.199654	1.799914	0.27	0.8971
Irrigation	3	2894.785975	964.928658	143.68	<.0001
sea*Irrigation	3	56.229008	18.743003	2.79	0.0504
rep*Irrigation(sea)	12	158.950179	13.245848	1.97	0.0485
Nitrogen	3	8127.755242	2709.251747	403.40	<.0001
sea*Nitrogen	3	6.382108	2.127369	0.32	0.8132
Irrigation*Nitrogen	9	613.497033	68.166337	10.15	<.0001
sea*Irrigat*Nitrogen	9	72.278133	8.030904	1.20	0.3196

Tests of Hypotheses Using the Type IV MS for rep*Irrigation(sea) as an Error Term					
Source	DF	Type IV SS	Mean Square	F Value	Pr > F
Irrigation	3	2894.785975	964.928658	72.85	<.0001
sea	1	75.260417	75.260417	5.68	0.0345
sea*Irrigation	3	56.229008	18.743003	1.42	0.2866

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	47	3287.208679	69.940610	5.81	<.0001

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Error	48	577.550717	12.032307		
Corrected Total	95	3864.759396			

R-Square	Coeff Var	Root MSE	HI Mean
0.850560	7.186133	3.468762	48.27021

Source	DF	Type IV SS	Mean Square	F Value	Pr > F
sea	1	8.366204	8.366204	0.70	0.4085
rep(sea)	4	378.131804	94.532951	7.86	<.0001
Irrigation	3	1271.966588	423.988863	35.24	<.0001
sea*Irrigation	3	125.430604	41.810201	3.47	0.0230
rep*Irrigation(sea)	12	324.323746	27.026979	2.25	0.0238
Nitrogen	3	173.423238	57.807746	4.80	0.0053
sea*Nitrogen	3	25.277404	8.425801	0.70	0.5565
Irrigation*Nitrogen	9	848.874971	94.319441	7.84	<.0001
sea*Irrigat*Nitrogen	9	131.414121	14.601569	1.21	0.3091

Tests of Hypotheses Using the Type IV MS for rep*Irrigation(sea) as an Error Term					
Source	DF	Type IV SS	Mean Square	F Value	Pr > F
Irrigation	3	1271.966588	423.988863	15.69	0.0002
sea	1	8.366204	8.366204	0.31	0.5882
sea*Irrigation	3	125.430604	41.810201	1.55	0.2533

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	47	871.042199	18.532813	1.65	0.0429
Error	48	537.833517	11.204865		
Corrected Total	95	1408.875716			

R-Square	Coeff Var	Root MSE	Dry Mean
0.618253	12.24614	3.347367	27.33406

Source	DF	Type IV SS	Mean Square	F Value	Pr > F
sea	1	28.8313760	28.8313760	2.57	0.1153
rep(sea)	4	42.6257708	10.6564427	0.95	0.4429
Irrigation	3	92.2123948	30.7374649	2.74	0.0533
sea*Irrigation	3	17.9808031	5.9936010	0.53	0.6606
rep*Irrigation(sea)	12	44.1930458	3.6827538	0.33	0.9801
Nitrogen	3	267.9721865	89.3240622	7.97	0.0002
sea*Nitrogen	3	35.7265115	11.9088372	1.06	0.3737
Irrigation*Nitrogen	9	165.7413510	18.4157057	1.64	0.1298
sea*Irrigat*Nitrogen	9	175.7587594	19.5287510	1.74	0.1050

Tests of Hypotheses Using the Type IV MS for rep*Irrigation(sea) as an Error Term					
Source	DF	Type IV SS	Mean Square	F Value	Pr > F
Irrigation	3	92.21239479	30.73746493	8.35	0.0029
sea	1	28.83137604	28.83137604	7.83	0.0161
sea*Irrigation	3	17.98080312	5.99360104	1.63	0.2351

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	47	1049.822917	22.336658	4.38	<.0001
Error	48	244.666667	5.097222		
Corrected Total	95	1294.489583			

R-Square	Coeff Var	Root MSE	nbt Mean
0.810994	11.32982	2.257703	19.92708

Source	DF	Type IV SS	Mean Square	F Value	Pr > F
sea	1	0.5104167	0.5104167	0.10	0.7530
rep(sea)	4	23.1666667	5.7916667	1.14	0.3508
Irrigation	3	203.0312500	67.6770833	13.28	<.0001
sea*Irrigation	3	31.0312500	10.3437500	2.03	0.1223
rep*Irrigation(sea)	12	103.5000000	8.6250000	1.69	0.0985
Nitrogen	3	494.9479167	164.9826389	32.37	<.0001

Source	DF	Type IV SS	Mean Square	F Value	Pr > F
sea*Nitrogen	3	9.1145833	3.0381944	0.60	0.6207
Irrigation*Nitrogen	9	98.3437500	10.9270833	2.14	0.0436
sea*Irrigat*Nitrogen	9	86.1770833	9.5752315	1.88	0.0782

Tests of Hypotheses Using the Type IV MS for rep*Irrigation(sea) as an Error Term					
Source	DF	Type IV SS	Mean Square	F Value	Pr > F
Irrigation	3	203.0312500	67.6770833	7.85	0.0037
sea	1	0.5104167	0.5104167	0.06	0.8119
sea*Irrigation	3	31.0312500	10.3437500	1.20	0.3518

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	47	8140.16667	173.19504	2.84	0.0002
Error	48	2929.16667	61.02431		
Corrected Total	95	11069.33333			

R-Square	Coeff Var	Root MSE	height Mean
0.735380	8.987696	7.811806	86.91667

Source	DF	Type IV SS	Mean Square	F Value	Pr > F
sea	1	640.666667	640.666667	10.50	0.0022
rep(sea)	4	1675.291667	418.822917	6.86	0.0002
Irrigation	3	356.083333	118.694444	1.95	0.1349
sea*Irrigation	3	589.916667	196.638889	3.22	0.0307
rep*Irrigation(sea)	12	1194.875000	99.572917	1.63	0.1143
Nitrogen	3	1773.083333	591.027778	9.69	<.0001
sea*Nitrogen	3	24.416667	8.138889	0.13	0.9397
Irrigation*Nitrogen	9	1084.500000	120.500000	1.97	0.0633
sea*Irrigat*Nitrogen	9	801.333333	89.037037	1.46	0.1906

Tests of Hypotheses Using the Type IV MS for rep*Irrigation(sea) as an Error Term					
Source	DF	Type IV SS	Mean Square	F Value	Pr > F
Irrigation	3	356.0833333	118.6944444	1.19	0.3542
sea	1	640.6666667	640.6666667	6.43	0.0261
sea*Irrigation	3	589.9166667	196.6388889	1.97	0.1716

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	47	521.7395833	11.1008422	5.15	<.0001
Error	48	103.5000000	2.1562500		
Corrected Total	95	625.2395833			

R-Square	Coeff Var	Root MSE	Branches Mean
0.834463	9.920344	1.468418	14.80208

Source	DF	Type IV SS	Mean Square	F Value	Pr > F
sea	1	5.5104167	5.5104167	2.56	0.1165
rep(sea)	4	5.1666667	1.2916667	0.60	0.6651
Irrigation	3	81.3645833	27.1215278	12.58	<.0001
sea*Irrigation	3	7.6145833	2.5381944	1.18	0.3283
rep*Irrigation(sea)	12	21.3333333	1.7777778	0.82	0.6250
Nitrogen	3	382.7812500	127.5937500	59.17	<.0001
sea*Nitrogen	3	0.5312500	0.1770833	0.08	0.9694
Irrigation*Nitrogen	9	9.5937500	1.0659722	0.49	0.8711
sea*Irrigat*Nitrogen	9	7.8437500	0.8715278	0.40	0.9267

Tests of Hypotheses Using the Type IV MS for rep*Irrigation(sea) as an Error Term					
Source	DF	Type IV SS	Mean Square	F Value	Pr > F
Irrigation	3	81.36458333	27.12152778	15.26	0.0002
sea	1	5.51041667	5.51041667	3.10	0.1037
sea*Irrigation	3	7.61458333	2.53819444	1.43	0.2831

Level of regimes	Level of nitro	N	yield		mark		nbt		hi	
			Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
ETC100%	N0	6	0.59500000	0.06833740	0.49333333	0.08310636	18.8333333	1.83484786	0.41000000	0.01414214
ETC100%	N1	6	0.70666667	0.05240865	0.60166667	0.05036533	22.5000000	2.58843582	0.47333333	0.01966384
ETC100%	N2	6	1.00333333	0.10911767	0.88166667	0.11267949	22.6666667	2.58198890	0.47500000	0.01378405
ETC100%	N3	6	1.22333333	0.12785408	1.13833333	0.14661742	24.0000000	3.22490310	0.43000000	0.02097618
ETC50%	N0	6	0.34333333	0.01632993	0.23500000	0.02880972	16.6666667	2.50333111	0.45666667	0.08238123
ETC50%	N1	6	0.55166667	0.04400758	0.43166667	0.02994439	15.6666667	0.81649658	0.56500000	0.05576737
ETC50%	N2	6	0.65000000	0.01897367	0.57500000	0.03391165	20.8333333	2.71416040	0.54833333	0.03188521
ETC50%	N3	6	0.73500000	0.01870829	0.62166667	0.03488075	20.8333333	5.87934237	0.57166667	0.04915960
ETC75%	N0	6	0.46333333	0.02338090	0.36833333	0.03763863	14.5000000	1.51657509	0.47833333	0.01602082
ETC75%	N1	6	0.71500000	0.10445095	0.63666667	0.02250926	17.6666667	1.21106014	0.50833333	0.02857738
ETC75%	N2	6	0.80500000	0.04969909	0.71500000	0.03507136	19.8333333	2.04124145	0.48833333	0.04119061
ETC75%	N3	6	0.98166667	0.05564770	0.91333333	0.02422120	22.5000000	2.73861279	0.52000000	0.02607681
ETC85%	N0	6	0.56333333	0.07474401	0.44833333	0.01940790	18.5000000	1.37840488	0.49666667	0.09157875
ETC85%	N1	6	0.75000000	0.07293833	0.65666667	0.08406347	18.3333333	1.03279556	0.40666667	0.05887841
ETC85%	N2	6	0.83166667	0.06210207	0.71666667	0.03326660	20.6666667	1.96638416	0.43666667	0.03265986
ETC85%	N3	6	1.08000000	0.04242641	0.98333333	0.04082483	24.8333333	1.16904519	0.45500000	0.02664583

regimes	nitro	nue LSMEAN	LSMEAN Number
ETC100%	N1	119.131667	1
ETC100%	N2	208.303333	2
ETC100%	N3	207.791667	3
ETC50%	N1	109.778333	4
ETC50%	N2	150.093333	5
ETC50%	N3	149.758333	6
ETC75%	N1	146.571667	7
ETC75%	N2	177.700000	8
ETC75%	N3	181.493333	9
ETC85%	N1	134.593333	10
ETC85%	N2	172.491667	11
ETC85%	N3	203.850000	12

Level of regimes	Level of nitro	N	wue	
			Mean	Std Dev
ETC100%	N0	6	7.1166667	0.79949151
ETC100%	N1	6	8.4316667	0.62636784
ETC100%	N2	6	11.9650000	1.28817313
ETC100%	N3	6	14.5966667	1.50488095
ETC50%	N0	6	8.2050000	0.39531000
ETC50%	N1	6	13.1750000	1.11650795
ETC50%	N2	6	15.4783333	0.55307926
ETC50%	N3	6	17.5233333	0.45680047
ETC75%	N0	6	7.3933333	0.36789491
ETC75%	N1	6	11.3700000	1.65131463
ETC75%	N2	6	12.8100000	0.78409183
ETC75%	N3	6	15.6200000	0.86167279
ETC85%	N0	6	7.8950000	1.04785018
ETC85%	N1	6	10.5100000	0.97246080
ETC85%	N2	6	11.6883333	0.85011568
ETC85%	N3	6	15.1266667	0.59828644

Level of regimes	Level of nitro	N	ch1		ch2		ch3		ch4	
			Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
ETC100%	N0	6	33.4933333	3.22781453	29.0400000	2.12007547	24.8800000	4.28106996	23.8566667	4.68130181
ETC100%	N1	6	35.7466667	1.82890860	32.5900000	2.60636912	27.0883333	5.87117166	25.2566667	6.44925939
ETC100%	N2	6	41.6566667	2.28092671	35.5466667	2.24013095	30.2033333	5.61843276	27.3883333	5.46325697
ETC100%	N3	6	50.5683333	5.23093650	41.7816667	2.89020703	35.8633333	6.22192789	32.0583333	5.39974598
ETC50%	N0	7	36.2771429	3.64415840	30.5000000	3.33594564	26.4171429	3.47384856	27.0842857	4.71534678
ETC50%	N1	6	40.9416667	2.43434933	34.9300000	2.43721152	32.1300000	2.82525043	30.0716667	1.63618357
ETC50%	N2	6	41.8700000	1.89859948	35.8583333	1.90108828	32.8950000	3.02727435	30.4783333	1.42984498
ETC50%	N3	5	43.8200000	2.05955092	37.8060000	2.06231181	35.3200000	2.41016597	33.0880000	0.60825159
ETC75%	N0	6	37.1916667	2.57341343	31.1800000	2.57382983	26.4033333	2.82594881	25.7516667	1.45777113
ETC75%	N1	6	41.6983333	1.42910345	35.6850000	1.43257461	32.6166667	2.66240242	27.7350000	1.37516181
ETC75%	N2	6	42.8366667	1.85740321	36.8250000	1.85964244	34.1016667	2.35087572	30.4483333	2.46741498

Level of regimes	Level of nitro	N	ch1		ch2		ch3		ch4	
			Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
ETC75%	N3	6	46.2800000	2.32177518	40.2683333	2.32007256	37.5466667	2.16333693	32.1550000	2.34707264
ETC85%	N0	6	39.5966667	2.66933450	33.5866667	2.66933450	27.8316667	3.35887134	25.5350000	1.96139491
ETC85%	N1	6	45.8750000	2.16919109	39.8633333	2.17119015	30.9800000	2.95135901	30.6883333	1.52833788
ETC85%	N2	6	47.1300000	1.80893339	41.1183333	1.81133560	33.7666667	1.64699322	31.2416667	1.16109288
ETC85%	N3	6	50.5083333	3.00017611	44.4966667	2.99821058	37.1850000	1.63007669	31.8650000	1.21485390

Least Squares Means for effect regimes*nitro. Pr > t for H0: LSMean(i)=LSMean(j). Dependent Variable: wue																
i/j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1		0.0139	<.0001	<.0001	0.0404	<.0001	<.0001	<.0001	0.5973	<.0001	<.0001	<.0001	0.1398	<.0001	<.0001	<.0001
2	0.0139		<.0001	<.0001	0.6650	<.0001	<.0001	<.0001	0.0502	<.0001	<.0001	<.0001	0.3067	0.0002	<.0001	<.0001
3	<.0001	<.0001		<.0001	<.0001	0.0231	<.0001	<.0001	<.0001	0.2575	0.1094	<.0001	<.0001	0.0067	0.5973	<.0001
4	<.0001	<.0001	<.0001		<.0001	0.0080	0.0951	<.0001	<.0001	<.0001	0.0010	0.0535	<.0001	<.0001	<.0001	0.3127
5	0.0404	0.6650	<.0001	<.0001		<.0001	<.0001	<.0001	0.1239	<.0001	<.0001	<.0001	0.5540	<.0001	<.0001	<.0001
6	<.0001	<.0001	0.0231	0.0080	<.0001		<.0001	<.0001	<.0001	0.0009	0.4861	<.0001	<.0001	<.0001	0.0057	0.0004
7	<.0001	<.0001	<.0001	0.0951	<.0001	<.0001		0.0002	<.0001	<.0001	<.0001	0.7866	<.0001	<.0001	<.0001	0.5021
8	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0002		<.0001	<.0001	<.0001	0.0005	<.0001	<.0001	<.0001	<.0001
9	0.5973	0.0502	<.0001	<.0001	0.1239	<.0001	<.0001	<.0001		<.0001	<.0001	<.0001	0.3391	<.0001	<.0001	<.0001
10	<.0001	<.0001	0.2575	<.0001	<.0001	0.0009	<.0001	<.0001	<.0001		0.0073	<.0001	<.0001	0.1034	0.5434	<.0001
11	<.0001	<.0001	0.1094	0.0010	<.0001	0.4861	<.0001	<.0001	<.0001	0.0073		<.0001	<.0001	<.0001	0.0348	<.0001
12	<.0001	<.0001	<.0001	0.0535	<.0001	<.0001	0.7866	0.0005	<.0001	<.0001	<.0001		<.0001	<.0001	<.0001	0.3472
13	0.1398	0.3067	<.0001	<.0001	0.5540	<.0001	<.0001	<.0001	0.3391	<.0001	<.0001	<.0001		<.0001	<.0001	<.0001
14	<.0001	0.0002	0.0067	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.1034	<.0001	<.0001	<.0001		0.0268	<.0001
15	<.0001	<.0001	0.5973	<.0001	<.0001	0.0057	<.0001	<.0001	<.0001	0.5434	0.0348	<.0001	<.0001	0.0268		<.0001
16	<.0001	<.0001	<.0001	0.3127	<.0001	0.0004	0.5021	<.0001	<.0001	<.0001	<.0001	0.3472	<.0001	<.0001	<.0001	